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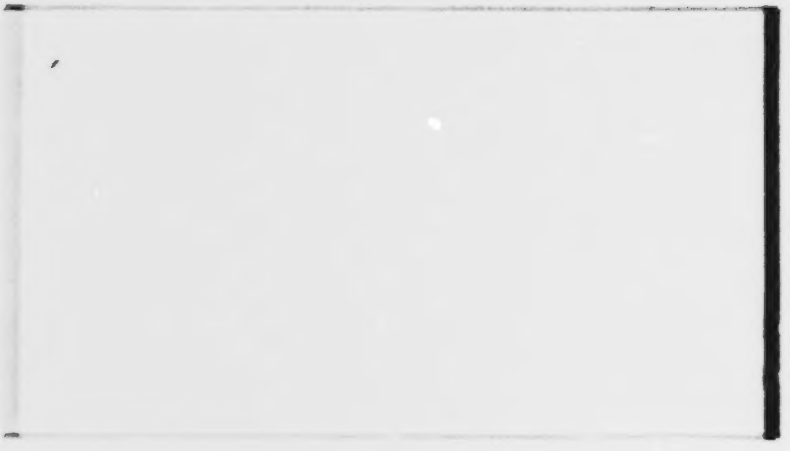

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# AN ASSESSMENT OF AUTOMATED PIPE WELDING - LITERATURE SURVEY

Report No. 86-27-K
Volume 1

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## ABSTRACT

This report describes the results of an extensive survey of recent developments in welding process control which might be considered in the establishment of an advanced mechanized pipe welding capability for use in Ontario Hydro. A review of the present status of mechanized pipe welding is given, together with examples of what techniques might be adopted to improve the performance of existing equipment. Current in-house activities in this area are described, including efforts to identify, with the associated cost benefit, potential applications in Ontario Hydro for an advanced mechanized pipe welding system, and the establishment of various work packages in a modular approach towards the development of such a system.



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## EXECUTIVE SUMMARY

# AN ASSESSMENT OF AUTOMATED PIPE WELDING - LITERATURE SURVEY

By:

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Past successes in the development and implementation of mechanized welding systems for plant construction and maintenance in Ontario Hydro have been achieved by recognizing the inherent shortcomings of existing techniques and limiting their use to a relatively narrow range of possible applications. The next step in our development of mechanized welding should be to overcome the limitations of the earlier systems so that they may be more widely used, for example for large-diameter pipe welding.

This report describes the results of an extensive survey of recent developments and new technologies which might be considered in the establishment of an advanced mechanized pipe welding capability for use in Ontario Hydro. A review of the present status of mechanized pipe welding is given, together with examples of what techniques might be adopted to improve the performance of existing equipment for welding of large diameter piping.

The report also summarizes current plans to identify potential applications for which an advanced mechanized pipe welding system might be used to advantage, and ongoing research in support of this development. When appropriate, a formal work program proposal is to be prepared which will provide a cost/benefit analysis, and will identify in detail the required work packages to establish an advanced mechanized pipe welding capability.

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To Mr. F.J. Kee
Director of Research

# AN ASSESSMENT OF AUTOMATED PIPE WELDING - LITERATURE SURVEY

## 1.0 INTRODUCTION

In the past, Ontario Hydro has had great success in applying mechanized welding techniques to plant construction and maintenance, especially in the nuclear plants. The impetus to introduce this technology has generally been the need to improve weld quality and productivity when a large number of identical welds have to be made, as in CANDU instrument tube or feeder pipe welding, or where access for manual welding would be extremely difficult, for example end fitting attachment bellows welding.

There are, however, applications to which conventional mechanized welding is less easily adapted, and one such case, for reasons outlined in this report, is welding of large pipes. Hundreds of welded joints must be made to ASME Code standards in large pipes during plant construction nevertheless. Pipe welding is also required in many plant maintenance tasks and in these situations, welding often must be done under difficult access conditions due to physical and environmental constraints. This welding is currently done manually.

A mechanized welding system developed for this kind of work would have many of the benefits obtained in the examples mentioned above. Furthermore, Ontario Hydro Welding Research Unit have accumulated expertise from involvement in other welding automation projects which could make a significant contribution to this area. A program to improve existing mechanized techniques to achieve a capability for welding large pipes is thus worthy of consideration. As a first step, an extensive literature survey was undertaken, covering recent developments in welding mechanization and automation which are potentially applicable to pipe welding.

This report presents the results of the literature survey. The full survey is given in Appendix A in Volume 2 of the report, and abstracts of selected papers of particular relevance are included as Appendix B. A summary of the present status of mechanized pipe welding is given in the report, together with a conceptualized description of techniques which may improve the performance of existing systems.

The literature survey was written with specific emphasis on repair and maintenance welding of nuclear plants. There is no technical reason, however, why an advanced pipe welding system should not be considered for general application in nuclear and thermal plants.

The report also outlines activities which are seen as prerequisites to any research and development program, and which should be carried out in the near future. These include: a formal exercise to quantify the probable costs and benefits of developing an advanced pipe welding system, and the formulation of program work packages.

## 2.0 SUMMARY OF LITERATURE SURVEY

### 2.1 The Current Status of Mechanized Pipe Welding

Bills of materials for power plants contain large quantities of piping of various sizes and grades. A large volume of pipe welding is required during plant construction, and many hundreds of joints must be made to ASME Code standards in large pipes. Replacement or modification of plant components is carried out from time to time, and much of this maintenance work also involves welding of pipes. In repair and maintenance situations, welding is often more difficult than the original operation, due to physical constraints and the existence of radiation or other environmental hazards.

Pipe welding has traditionally been done manually. Manual pipe welding procedures are well-established in Ontario Hydro, and there is no doubt that they have the advantages of flexibility and simple, low-cost equipment. All that is required is a power supply and welding gun, and access for the welder to manipulate the gun around the joint (Figure 1).

Mechanized pipe welding equipment is by comparison much more complex. Existing mechanized techniques for welding power piping are mostly based on the Gas Tungsten Arc (GTA) welding process. Typically, the welding torch and filler wire feed mechanism are carried by a motorized welding head, which rotates around the joint on a track clamped to the pipe. The welding head is connected by cables to a welding power supply and control panel, on which the necessary sequence of functions to execute the procedure is preprogrammed. Procedures are generally derived from trial-and-error experimentation. Once the parameters have been set up and the equipment is in operation, the welding operator must closely supervise the process and make adjustments as necessary. For remote-controlled operation in nuclear plants, welding heads have been fitted with miniaturized TV cameras and microphones to give the distant operator some feedback from the process. Such a system, typical of what has been used for nuclear pipe repair in US and Japanese plants, is illustrated schematically in Figure 2.

In spite of their apparent complexity, mechanized pipe welding systems have been increasingly used by the energy and petrochemical industries worldwide over the last few decades, and equipment is commercially available from a number of suppliers in the US and elsewhere. Mechanized pipe welding is generally perceived to offer precise control of the welding parameters, thereby improving weld quality over the long run, and to improve productivity, since the machine obviously does not tire as a manual welder might. Once set up, the equipment can be operated semi-remotely, which is desirable for work in hazardous or unpleasant environments.

It has become evident, however, that existing mechanized pipe welding techniques have drawbacks which tend to impair their usefulness. The major problems stem from two facts: (i) the welding sequence is preprogrammed, and (ii) the adjustments that can be made even with an operator in close attendance, are somewhat limited.

These are characteristics of conventional mechanized welding technology generally. Most successful mechanized applications depend on one or more of the following:

(i) precisely defined weld preparation geometry
(ii) good fit-up and alignment between the mating parts
(iii) the use of the easily-controlled, but very slow, GTA welding process
(iv) an on-site operator to closely monitor the process and override it if necessary

It is inherently difficult to work around the above four limitations when welding large pipes. Rough preparations and approximate fit-up, part of normal construction, are completely unsuitable for mechanized welding. Preparation and fit-up tolerances from a typical mechanized pipe welding procedure are shown in Figure 3. The pipe ends can be prepared to close tolerances using portable lathes, but obtaining good fit-up is always problematical, especially when performing pipe tie-ins (final joints between pipes fixed at their other ends).

Large pipes are of necessity welded with multi-pass procedures, as illustrated for instance in Figure 4. Multi-pass welds involve tracking the joint as it is progressively filled, taking into account changes in groove cross-section with thickness, distortion, and mismatch caused by pipe diametral tolerances. Automatic arc gap controls which are common on commercial pipe welding systems correct for radial tracking errors only. The on-site operator can make some adjustment to torch position based on what he sees, but overall control is rather hit-and-miss, and is even less efficient in remote situations where feedback from the process is sparse. Furthermore, the low deposition rate of the GTA process is a distinct disadvantage, which is barely offset by the higher duty cycles that can be achieved by mechanization. There are higher deposition variants of the GTA process, such as hot wire (HW-GTA) or narrow gap procedures, but these are rarely used in practice because they tend to be even more sensitive to external disturbing factors.

As stated, the major problem areas with current mechanized welding pipe methods stem from the limitations of preprogrammed, sequential process control, which result in poor tolerance to variation in external factors. It is far from definite that merely adding more functions and programming steps to existing controllers would do anything to resolve this, because the real problem is how to make the machine interact with the unstructured variability in the environment. If it were possible to make

the process adaptable to external factors, something of the flexibility and dexterity of the manual welder which is lost in crude mechanization would be recaptured. Adaptive control would be expected in general to yield benefits of relaxed tolerances on preparation and fit-up, less operator servicing of the welding head, fewer weld defects requiring repair and reinspection, and the possibility of using higher-productivity processes such as pulsed-current Gas Metal Arc Welding (p-GMAW) or HW-GTA to reduce welding cycle times.

## 2.2 Recent Advances in Welding Process Control

The economic advantages of automation have led industry to install a small, but increasing number of arc welding robots and positioners, which are typically used in batch manufacture of light and medium components such as earthmover frames, truck axles, office furniture, etc. The first generation of welding robots however suffers from some of the drawbacks associated with mechanized pipe welding equipment. Welding robots are nothing more than programmable manipulators, and while they have great flexibility in the sequence of actions they can be programmed to do, once programmed for a specific sequence, they are every bit as 'dumb' as more lowly devices. The robot may be capable of accurately following a given trajectory and delivering a precise set of welding conditions, but this precision is to no avail if workpiece geometry and fit-up vary as a result of manufacturing and fixturing tolerances. It is not always cost-effective to insist on tight part tolerances to suit the welding process. Making the process capable of adaptation to variations in the workpiece is a longer-term solution, and adaptive control therefore has become a major topic for research in 'second generation' welding automation.

Many different types of system in fact require some form of adaptive control to operate successfully under changing conditions. Take for example a building's heating plant, which uses a thermostat to turn the heating off or on as the temperature of the room rises and falls, as illustrated in Figure 5. Note that the thermostat is not shown as a single element because it has two functions: (i) to measure the temperature of the room and (ii) to decide whether to turn the furnace on or off. Such a system is used because variations in the outdoor environment would otherwise cause unpredictable changes in room temperature. If outside conditions such as temperature, wind and solar heating which represent the load on the system could be predicted, then we could design a heater that would operate at a predetermined rate just large enough to replace heat lost to the outside. No control system would be necessary.

Welding processes are more complicated than the simple heating plant analogy just given, because the system output is measured directly in terms of several variables rather than one, such as bead geometry, strength, and the presence of defects, and the outputs are affected by a number of input parameters and environmental factors (Figure 6). The

complexity of the situation when the outputs, intermediate process variables and environmental factors are considered as potential candidates for feedback control is illustrated by Figure 7.

In the heating plant analogy, it is clear what variable should be regulated (temperature), and the control logic is just about as simple as it can get (if the temperature is too high then turn the heater off, and vice versa). Such is not the case in welding. It is often not clear what welding variables should, or indeed can, be measured, nor what control action should be taken on the sensory data. No general solution has as yet emerged, and it seems that the control strategy must be built up for each case using the specifics of the application and expert knowledge based on theory and experiment.

Recent advances in welding process control generally can be grouped into the five categories of:

(i) seam tracking
(ii) bead geometry/penetration control
(iii) groove fill control
(iv) expert systems
(v) man-machine interface

Developments in these areas are summarized very briefly below. The reader interested in further reading should refer to the Appendices in Volume 2.

### 2.2.1 Seam Tracking

Seam tracking is a problem common to nearly all mechanized arc welding applications, and numerous methods have been developed using, for example: mechanical contact followers, eddy current transducers, fluidic proximity sensors, ultrasound, arc electrical signatures, laser triangulation and video image analysis.

It is important to distinguish between techniques that are applicable only to single-pass welds and those which can be extended to multi-pass welds. With simple weld types, such as single-pass welds in square-butted plates, the joint can be characterized essentially as a line, and the tracking method can rely upon geometric features of the joint which exist before welding, even if they are obliterated afterwards. Multi-pass welds are not simple because of the need to see the groove in three dimensions, and because the welded surface is less distinct and is constantly changing.

Arc electrical signature analysis (sometimes called 'Through-Arc Sensing') has been successfully used as a seam tracking technique in recent mechanized welding systems employing either the GTAW or GMAW process for multi-pass welds. A system using Through-Arc sensing is offered commercially by CRC of Nashville, Tennessee.

The basis of the technique is the introduction of a cross-seam oscillation to get interaction between the arc and the groove sidewalls (Figure 8). The torch is driven across the weld groove, and the system 'listens' for the electrical disturbance as the arc encounters the sidewall (a voltage drop in GTAW or a current rise in GMAW), which triggers a reversal in cross-travel direction. The process is then repeated indefinitely, causing the torch to oscillate along a groove of arbitrary width in a series of zig-zags. Arc length control is effected by sampling arc voltage or current as the torch traverses the quiescent mid-point of the groove. A variant for GTAW is to monitor movement of the arc length control servo, rather than to measure voltage directly. Setting tolerance bands for estimated sidewall position, which can be updated interactively using a moving-average technique, and within which cross-travel reversal is constrained to occur, has been found to prevent failures caused by missed or spurious signals. Reading data recorded from previous passes is employed as a way of tracking the final pass, when the groove edges have become indistinct.

In laser triangulation techniques, a narrow beam of light emitted from a laser diode is scanned across the workpiece surface and reflected light is focussed upon a detector, from which the location of the surface can be determined by triangulation (Figure 9). After processing the returned signal, the edges and apex of a typical V groove preparation can be accurately located (Figure 10), and the availability of complete surface profile information enables not only seam tracking, but also permits monitoring of groove fill and bead placement. The Industrial Materials Research Institute (IMRI) of the National Research Council of Canada, located near Montreal, has been doing R&D work in laser triangulation technology as it pertains to welding for some years. A product of this effort was the establishment of the Montreal-based company Servo-Robot Inc., which is marketing a laser sensor system for welding thought by many to be one of the most advanced systems currently available. The CEGB (UK) are also investigating commercially-available laser triangulation devices for remote welding applications.

Video image analysis is really a group of techniques that allow surface topographical information to be deduced from a TV image of the weld zone. The most basic technique uses changes in the gray level of a video frame line to estimate the position and width of a high-contrast feature such as a weld root opening (Figure 11). A way of furnishing depth information in a video image is to project a sheet of bright light at an oblique angle to the workpiece. The intersection of the light and the surface when viewed from another angle represents a cross-section of the surface, which can be detected automatically using contrast-difference techniques, and the true surface profile may then be computed by triangulation (Figure 12). State-of-the-art systems such as that of Automatix of Billerica, MA, can resolve minor features like the wetting

points between the weld deposit and the sidewalls, and again the availability of surface profile data permits higher-level control, e.g. monitoring of bead placement and groove fill, as well as seam tracking. A particular advantage of video techniques is that an ordinary TV picture of the weld zone is available and can be presented for human interpretation in addition to the sensor system output.

### 2.2.2 Weld Bead Geometry/Penetration Control

The major application for bead shape control in multi-pass welds is on the root pass, where control must be quite delicate in order to maintain full penetration and an acceptable bead profile. Essentially, two approaches for bead shape control have been developed.

One approach is to directly measure weld pool size or shape with some sensing device, on the basis of which welding parameters such as pulse time, welding current, or travel speed are automatically adjusted to maintain consistent penetration. Optical sensors are mostly used to measure weld pool size, either high-resolution systems combined with image analysis to detect the weld pool outline, or photodiodes that respond to the gross level of infrared radiation emitted from the weld zone, which is roughly proportional to weld pool area. For the root pass, the sensors can be placed on the underside of the weld, provided there is access, to measure penetration. One of the better-known examples of this technique, using infrared photodiodes, was developed by the CEGB in the 1970's, and equipment is currently marketed commercially in the UK (Figure 13). Sensors mounted on the top of the weld can also give an indication of root penetration if the relationship with pool top surface size is known. Hydro Quebec have done promising work in this area, and ongoing work at IMRI, in conjunction with the Welding Institute of Canada's Quebec Centre, is continuing to advance this technology.

Many other ingenious techniques for measuring weld pool size or detecting penetration, for example using ultrasonic probes or monitoring the oscillatory response of the liquid pool, have been explored at a research level, but have not yet achieved any advanced stage of development.

The second broad approach to controlling weld bead geometry, known as "Adaptive Welding Procedure Selection" after work at the UK Welding Institute, is to make anticipatory adjustments to the welding parameters in response to sensed changes in a known disturbing factor. Most welding engineers will for instance be familiar with the need to reduce current as root gap increases, or again to compensate for changes in orientation with respect to gravity when welding around a pipe, in order to maintain constant root penetration. Interactive control is possible if the disturbing factors are measured on-line, and if the controller is programmed to make appropriate adjustments to the welding parameters.

Control in this scheme depends on having a reliable model of the process behaviour, and in the absence of theoretical information, process models are often based on factorial experiments conducted in the neighborhood of a chosen procedure. The results of these experiments, in the form of regression equations or qualitative 'tolerance boxes' (Figure 14), can be interpreted to indicate suitable welding parameters for each level of the disturbing factor, assuming that such exist (e.g. Figure 15), thus providing the basis for control rules. There have been several demonstrations of Adaptive Procedure Selection, to control of root bead geometry in response to fit-up variations in Flux Cored Arc welding, for example. The technique is successful for the case of one or two independent variables, although it tends to become too involved when several variables must be considered simultaneously.

### 2.2.3 Groove Fill Control

When preparation and fit-up are less than ideal, the groove cross-section varies along the axis of the weld, leading to the problems of depositing an appropriate bead sequence and avoiding local areas of overfill or underfill.

There have been production examples involving single- or two-pass welds where the fill has been adjusted automatically in response to varying groove cross-section by surveying the groove before welding with an optical device (see above), then adjusting travel speed or filler wire feed speed appropriately as the joint is traversed. Consideration of the bead deposition sequence is of course absent in such simple cases, and is a factor which makes multi-pass welds in thicker sections more difficult.

Hitachi have developed a mechanized GTAW system for repair of nuclear piping (Figure 2) which includes advanced features for control of the fill passes. A full-weave procedure is employed, which results in a bead structure consisting simply of layers of filler metal across the width of the groove. How seam tracking is performed is not known exactly, but it could clearly be done using the 'Through-Arc' system. Welding parameters are selected automatically by a control algorithm (which is depicted in Figure 16) that takes account of limits on current as a function of welding position, limits on wire feed speed as a function of current and heat input, etc. A "magnetic tracer" monitors surface profile after each pass and feeds data back to the control computer. The operator is also provided with a TV image of the weld zone which he can use to make minor adjustments to the process.

The CEGB have been experimenting recently with a system for multi-pass mechanized pipe welding using the p-GMAW process. This system is designed to be able to interactively plan a bead deposition sequence and to control groove fill in preparations of irregular shape. The system uses a laser rangefinder to survey the initial groove profile, from which

a bead sequence is automatically planned according to rules formulated for the particular joint type. Welding parameters are selected automatically, to adjust bead size to fit the planned sequence, on the basis of an empirical process model. The equipment then proceeds to execute the planned sequence until it is nearly complete, when the joint profile is resurveyed, and corrections are made throughout the final passes to bring the weld flush with the outer surfaces. Although the CEGB development is still at an early stage, weld samples have been produced.

### 2.2.4 Expert Systems

'Expert Systems' are computer programs which contain a codification of expert knowledge in a particular field and which are designed to provide solutions to given problems.

Although they may not be loudly heralded as such, several of the adaptive control techniques outlined in the preceding sections are embryonic expert systems. They deserve this title because the control decisions are made by computer software 'algorithms' which are written on the basis of detailed knowledge of the welding process behaviour and the application context. Take for instance Figure 16, which shows the decision flow chart for pipe fill pass welding with the Hitachi system. The algorithm takes account of diverse constraints on process operation which follow from theory, experiment and practical considerations, and within these constraints selects welding parameters suitable for the particular conditions.

Expert system and sensor-equipped computer control is considered to have great potential in adaptive control of mechanized welding because of the flexibility it offers in writing control schemes. Hardware problems (the design of sensors, for instance) are merely the tip of the iceberg, however. The major issue is design of the software - the customized logic for control - which will require something of a marriage between computing and welding engineering skills.

As higher-level control functions are automated, the software developer needs to determine what functions the software is to perform and to envisage the different situations to which the software must respond. Specification, or deciding what functions should be performed at what time, becomes more difficult as the task grows in complexity, and while there is no theoretical limit, there is probably a practical limit on what it is possible to do.

### 2.2.5 Man-Machine Interface

Although the trend reported above is to automate various process control functions, the operator is still expected to exert overall, supervisory control of the system in most cases. It is important to make provision for this.

Developments in this area have mainly been confined to providing a video image of the weld zone, to permit the operator to make minor adjustments to torch position or welding current from the control panel. Providing a good-quality picture is not a trivial problem, because the high light output and contrast of the weld zone make it a difficult photographic subject, and fibre optics and miniature cameras must be used to keep the welding heads reasonably compact. Some video systems are commercially available, and the UK Welding Institute has done work on weld video techniques which is available to Research Members as a report package. AECL is currently a Research Member of the WI. Microphones are sometimes fitted to the welding heads to feed back the sounds emitted by the arc, which can usefully augment the operator's interpretation of a video image.

Remote controls are provided on most machines which allow limited manual override of parameters such as welding current and torch position. Some mechanized pipe welding units have been equipped with motorized adjustment of the torch and the wire feed guide nozzle, permitting the correct alignment to be maintained remotely.

## 3.0 APPLICATION OF ADVANCED PROCESS CONTROL TECHNIQUES TO MECHANIZED PIPE WELDING

### 3.1 General

Recent trends and developments in welding automation have been summarized in the preceding sections; their application to improvement of existing mechanized pipe welding techniques is discussed below.

The techniques and approaches to process control outlined above may be regarded as solutions which it is at least feasible to consider in the design of an advanced mechanized pipe welding system, even if it is clear that R&D effort will be required before many of the concepts can be implemented. It should be noted that a multi-pass welding procedure is a complex series of activities, rather than a "one-shot" operation. Consequently, mechanizing the procedure is not necessarily a matter of finding a single technique, and we should probably think instead of using different techniques as appropriate. In order to see which solutions may be employed to advantage, it is necessary to consider in detail the problems that exist at each stage of the procedure.

There is also an obvious dependency on the type of welding process that is employed; in fact, the choice of welding process is a variable in the design problem. The GTAW process is used in most mechanized welding procedures for nuclear piping, and the technology is well-developed, but its disadvantages are also clear. It is possible that the pulsed-current GMAW process may form the basis for a mechanized pipe welding system. The Welding Unit at Ontario Hydro Research has made a significant contribution to the development of this process for mechanized heavy-section repair and manual applications, and has acquired a good understanding of the process characteristics. Pulsed GMAW offers relative ease of control for out-of position welding, attractive deposition rates, and a simple welding torch arrangement compared to, for instance, HW-GTAW.

With this preamble, the multi-pass pipe welding procedure is seen as consisting of three stages with distinct control problems at each stage, namely: the root pass, the fill passes, and the capping passes.

### 3.2 Root Pass

The major problems of the root pass are: tracking a seam with displacements in both the radial and axial directions; and the need to ensure full penetration and acceptable bead contours in spite of changes in orientation with respect to gravity and variations in preparation geometry, including different combinations of root face, root gap, and mismatch (e.g. Figure 17).

### 3.2.1 Seam Tracking

Seam tracking is the more easily surmounted of the two problems given the number of proven techniques that exist, although developmental work will be required before they can be applied specifically to pipe welding in Ontario Hydro. The leading possibilities are: tracking the seam by optical imaging; the Through-Arc technique of tracking with respect to the groove sidewalls; or tracking according to surface profile measurements to identify the centre-line of the groove. The choice depends somewhat on the application: for instance, the Through-Arc method can only be applied to V-groove or narrow-gap preparations in which a slight weave will give the necessary interaction with the sidewalls. In close-fitted land-type preparations, the seam may be effectively invisible to contrast-based optical methods.

Video-based techniques offer the greatest overall capability, since tracking can be based on either identifying the root gap with an image contrast analysis technique (Figure 11), or on measurement of the surface profile with the addition of structured light aids (Figure 12), and further because an ordinary TV picture can be presented for human interpretation to augment the automated system. A weld video system with computer image analysis also serves well the needs of other stages of the welding procedure, as discussed in following sections.

A video-based seam tracking system would thus be a desirable choice in principle. Few video seam tracking systems are commercially available at present, although it may be possible to purchase components. Thus, significant research and development work will be required to put the video system into practice, beginning with an assessment of the speed and resolution required and attainable in general, since sufficient detail is not available from the present literature survey. Major topics for subsequent work are: determination of suitable weld zone photographic techniques and equipment, development of image analysis computer programs, and associated control interfaces. A prototype will likely have to be built with which to gain necessary practical experience in these areas.

Through-Arc sensing would be useful for root pass seam tracking if V-groove or narrow-gap preparations are used, and would be useful for fill pass control in any case. It may be possible to purchase this technology, notably from CRC Corp. of Nashville, Tennessee. Being also somewhat simpler than a video system, the Through-Arc technique would be more easily developed over the short term, but it ultimately has the lesser utility.

### 3.2.2 Root Pass Penetration Control

Control of root pass penetration and bead profile to meet ASME Code standards is a more difficult problem than seam tracking, as fewer techniques have been successfully applied. This is a critical area where

progress must be made if improvements are to be achieved in broadening allowable tolerance ranges for end preparation and fit-up.

There are extremes of misfit beyond which a given welding process will break down. It is not, for instance, reasonable to think of welding a ½-inch root gap with a single GTAW pass. The objective of installing adaptive control might therefore be to extend the present very tight tolerances on preparation and fit-up to the limit of what is naturally possible. Some welding processes or procedures will possess inherently better tolerance to fit-up variations than others, and it would clearly be beneficial to choose such a process or procedure as the subject for control in the first place. It is not possible to predict from theoretical grounds how different processes or procedures will react to fit-up variations, and there is both a need and considerable scope for empirical research in this area.

One type of root pass penetration control system outlined in the review measures weld pool size or some related variable directly and makes continual adjustments to heat input to maintain constant penetration. The CEGB system using photodiodes on the underside of the weld is a possibility when there is access inside the pipe to mount the sensors. If the welding machine is equipped with a video system, it would also be logical to measure weld pool size by image analysis, as has been demonstrated by Ohio State University.

Systems of this type can be effective in compensating for changes in material thickness or other heat flow conditions. A weakness, however, is that they rely on a stable weld pool being formed. Large gaps or mismatch in practice may result in loss of the weld pool, which cannot be remedied by adjusting heat input alone if the abutting edges are so far apart as to prevent the liquid metal from bridging the gap. If loss of the weld pool occurs as a result of a large gap, experience indicates that it tends to happen quickly, with little in the way of visual precursors, and so the time available to sense changes and take corrective action before a defect is created is very short, possibly of the order of milliseconds. No direct weld pool control system is known to have been developed which can work within these conditions.

The alternative approach for root pass penetration control is the adaptive welding procedure selection method, in which the disturbing factors themselves are measured, and anticipatory adjustments are made to the welding process by what is in effect an 'expert system' controller. One advantage of this approach is that if root gap, for instance, is measured some way ahead of the advancing weld pool, there is considerably more time, of the order of seconds, for the controller to take action. A further advantage is that the controller may be programmed to make completely arbitrary and even radical responses. For example, there is no reason why, on encountering an increased gap, the controller might not

simultaneously order a torch weave motion, a reduction in current, and an increase in wire feed. The possibility of completely changing the welding procedure in this fashion to suit local conditions may allow the welding process to cope with larger variations in gap and mismatch.

On the negative side, such a system can fail if some factor which is not measured as part of the control scheme unexpectedly turns out to be critical under some combination of conditions. As an example, the effect of material composition on weld penetration characteristics quickly comes to mind.

The apparent flexibility of expert systems is simply a reflection of the fact that it is the welding engineer-cum-software developer who determines the response. In other words, the engineer must envisage the situations to which the software must respond and determine appropriate actions. This knowledge will require experimental observation under the conditions of a given application.

Root gap and mismatch may be determined for adaptive control of the welding parameters by optical means, and this would be the preferred method assuming that the welding head is equipped with an "intelligent" video system as described above. It is not clear how root face could be measured in a fitted up joint and, if need be, ways of doing so require investigation.

### 3.3 Fill Passes

The major technical problems of making the fill passes are: planning and depositing a suitable bead sequence while maintaining good wetting and tie-in, compensating for changes in groove cross-section around the pipe circumference, and tracking the joint with relatively large displacements (of the order of one pipe wall thickness) in the radial and axial directions as the groove is progressively filled.

It is unlikely that it will be possible to devise a system giving moment-to-moment control of the welding parameters for adapting to minor features of the surface being welded, because of the difficulty of accurately resolving such features and the effectively limitless number of permutations. The foundation of the fill procedure must therefore be a set of welding parameters which gives stable arcing conditions, good fusion with underlying passes, and a suitable surface for subsequent passes. Determining such parameters is a conventional welding procedure development exercise. Existing standard procedures may suffice.

Seam tracking requires current information on the location of the welded surface and the groove sidewalls. This data can be obtained optically, and since a video system is seen as an essential component for other purposes, this would again be the preferred choice. Note that the Through-Arc method could also serve for fill pass seam tracking if a weave procedure were employed.

Compensation for variations in groove cross-section involves taking into account both the original profile and significant shrinkage and distortion which occur as the weld is completed. Thus, periodic surveys of the partly-completed weld will be needed, and it is envisaged that these surveys may be carried out using the structured light video system. Whether update surveys will be required after each weld pass, or at less frequent intervals, depends on how accurately the weld build-up can be predicted, which is a subject for investigation. Once surface profile data from around the pipe circumference have been obtained, it is relatively simple to make proportionate adjustments to the amount of filler metal added at each point to maintain even fill.

Planning and execution of the bead deposition sequence to suit a particular joint is a high-level function on which many constraints and optimization criteria exist. Although the CEGB have had some success in this area, it is difficult to imagine a system in which the bead deposition sequence is completely removed from the control of the operator. It is questionable whether such complexity is necessary.

It is considered that the better alternative would be to design a system in which the operator has overall supervisory control of the process and to provide automated subroutines to improve system performance and lessen the operator workload. These routines might include for instance full cross-seam oscillation using the Through-Arc sensing method, a split-weave from the groove edge to a fixed position commanded by the operator, or stringer bead deposition at operator-input locations.

Man-machine interfaces are essential to facilitate these operator controlled functions, and foremost among these is good video presentation of the weld zone. Added to a basic video system, computer-generated graphics offer a number of interesting possibilities. Bead positioning might for instance be controlled by the operator using electronic cursors or pointers superimposed on a video image of the weld. The control computer could also keep track of the number of passes deposited and update and display the current groove cross-section. Control data presentation and prompting of the operator in this way is a fertile field for innovative design.

### 3.4 Capping Passes

Once the weld is nearly complete, the major issues that have to be dealt with by an automated system are tracking the joint and filling any areas of underfill caused by pipe diametral variations.

When the weld nears completion it becomes almost flush with the surrounding material, resulting in the loss of the distinctive features that enable the seam to be located by surface measurement or the

Through-Arc methods. The weld will in general be visually evident, and probably the easiest way of locating the seam would be by operator remote control using a viewing system. An alternative would be to read position data recorded on previous passes.

Patching areas of underfill requires a cavity-profiling device and a welding algorithm. The video structured light system is again seen as the logical surface measuring device. The problem of filling in the measured cavity is within the bounds of recent OHRD work on automated heavy-section repair.

## 4.0 FUTURE WORK PLANS

This report so far has outlined the major problem areas in conventional mechanized pipe welding methods, has reviewed recent technological developments in welding mechanization and control, and has attempted to illustrate how these recent developments can be beneficially applied. The findings of the literature survey suggest that Ontario Hydro's present pipe welding capability can very likely be enhanced by the addition of advanced control techniques to the mechanized pipe welding techniques currently in use.

A substantial research, design, and development effort will be needed to put the concepts outlined in the literature survey into practice. It is unlikely that welding equipment suppliers (e.g. Arc Machines or Dimetrics) on their own will undertake all the necessary effort to produce such equipment for power plant pipework because of the high cost of development and the rather limited sales prospects. To obtain the predicted benefits, end-user utility companies likely will have to shoulder some of the R&D costs, possibly working with other utilities, research and manufacturing organizations.

The elements of any proposed R&D program will naturally depend on information gained regarding our perceived needs, as well as in-house expertise with respect to advanced welding processes and equipment, and continuing development worldwide. The Welding Unit of the Metallurgical Research Department has for several years engaged in research and development work in welding automation and advanced welding processes. Most recently, this has led to the establishment of a collaborative program with Hydro Quebec, partly funded by the Canadian Electrical Association, to develop a prototype robotic welding system for in-situ repair of hydraulic turbine runners. The technology and expertise derived from this program will be an important resource for advanced pipe welding system development.

Relevant development work is also continuing in other quarters, and advancement may best be gained by establishing informal and/or formal relationships with these groups. Collaboration with IMRI might be promoted, for example, to have the laser sensor and image processing expertise developed there applied specifically to our pipe welding root pass problem, with our in-house work concentrating on the data base required to establish appropriate control algorithms. Contact with such organizations as well as the commercial suppliers will help determine the best time for acquiring such a system for in-house testing and optimization.

## 4.1 Cost-Benefit Studies

Decisions clearly have to be made as to the value of committing funding and effort to research on advanced pipe welding techniques. These decisions should be based on a good understanding of the shortcomings of existing pipe welding technology in the utility environment, and the attendant benefits of an advanced pipe welding system.

The ongoing CEGB work on a highly-automated pipe welding system provides a good example of the forward looking approach that Ontario Hydro should try to emulate. Hydro has followed leads taken by the CEGB in the past, for instance on thermal plant transition joints and temper bead repair work. The fact that the CEGB is engaged in welding automation is an indication that benefits are to be gained.

It is intended that a survey be conducted across the Corporation regarding potential areas in Hydro's plant where an advanced pipe welding system could be used to advantage. Information will be collected on costs and technical problems that are encountered using existing manual or mechanized pipe welding techniques. The information collected is to be used for cost-benefit analysis and, if the general perception of field personnel supports further action, to prepare a detailed work program proposal for development of an advanced pipe welding capability in Ontario Hydro.

## 4.2 Components of Proposed R&D Program

It is evident from the literature survey that there are a number of alternative techniques that may be applied to mechanized pipe welding. Arriving at a specification that is in some way optimum is a matter for careful design. It is also clear that a highly-automated system will require advances on a number of broad technological fronts. Thus it is difficult to plan a research and development program that will lead directly to the realization of such a system in the short term. At present, it is felt that Hydro's welding needs might best be served by establishing a series of work packages which generate information or capabilities that are of immediate benefit to the Ontario Hydro welding community, while forming part of the longer range strategy. Several topics meet this criterion,as follows. Initial concentration on topics such as these, which have short-term spin-off benefits, deferring work on technology specific to pipe welding until they are firmly in place, will tend to maximize the value of the research.

(1) Process/Procedure Tolerances to Fit-Up Variations: Identifying welding processes and procedures which are inherently tolerant of pipe fit-up and positional variations, and finding ways in which the procedures may be modified to compensate for local extremes of misfit, were identified as critical needs. A limited program has already begun to generate data for GTAW root pass tolerance to fit-up variations. For

a range of welding parameters, the influence on weld deposit geometry of variations in fit-up (e.g. gap and mismatch) and welding position are to be evaluated. The eventual objective is to generate sufficient information to enable an expert system controller to automatically select suitable welding parameters for the local conditions around the pipe. This work will be of immediate benefit also, by providing a scientific and quantitative basis for welding procedure selection in existing mechanized GTAW applications.

The pulsed-current GMAW process is seen as a desirable alternative to GTAW for a mechanized welding system. A work package similar to the above will be required to generate information for automated control, but also would provide substantial spin off benefits before completion of the overall mechanized pipe welding program.

(ii) Remote Viewing: A high-quality television system for viewing the weld zone is an essential requirement for an automated remote-control pipe welding system to give the human operator feedback from the process. A capability in remote viewing of welding processes would however find ready application in other tasks where remote-controlled mechanized welding is required, such as in repairs to operating nuclear plants, encapsulation of radioactive waste, or heavy water plant vessel repair.

(iii) Surface Modelling: The ability to automatically image the surfaces of the components being welded is necessary for automatic seam tracking and control of groove fill. This is true of automated applications other than pipe welding, as evidenced by the volume of recent work on this topic for general robotic applications.

Computer-assisted analysis of images from the weld zone viewing system was seen in earlier sections of the report as being a logical choice of method. Techniques in this area are developing rapidly, and there is a need to keep abreast of developments.

Laser triangulation is a viable alternative to video image analysis for surface modelling, and it would therefore be beneficial to continue to explore developments in this area also.

(iv) Through-Arc Sensing: Through-Arc sensing as a seam tracking technique has been commercialized, and can be incorporated fairly easily in existing GTAW welding heads, both for pipe welding and general application involving welding of fillet or groove geometries, and thus would be of general benefit.

## 5.0 CONCLUSIONS

1. Welding of pipe or tubular products is a significant activity during both construction and maintenance of nuclear and thermal generating stations. Much of this welding is currently done manually, because commercially-available mechanized welding equipment has a number of general shortcomings. Principally, there is no effective mechanism for control of the process under varying conditions. This means that existing preprogrammed machines exhibit relatively poor tolerance to external factors, inaccuracies in pipe end preparation for example. Consequently, welding takes a greater expenditure of time and man-rem than might be technically achievable, due to tight tolerances on end preparation and alignment, lower welding speeds, greater operator servicing of in-situ equipment, and repair and reinspection of defective welds.

2. Ongoing research worldwide has resulted in a number of technological developments in welding mechanization and control, in the form of techniques and products whereby a welding process can be made to adapt to external factors. The findings of the present literature survey suggest that Ontario Hydro's present pipe welding capability can likely be enhanced by the addition of adaptive control techniques to existing mechanized systems.

3. Pipe welding procedures are not simple, one shot operations, but are complex sequences of activities. There is no single product or idea that alone transforms a mechanized welding process into an adaptive one: no general solution is in sight and nor is one expected. Realizing an advanced pipe welding system is a matter of correctly identifying key problems at each stage of the welding procedure and designing effective solutions for them. The overall framework suggested is to assign high level control and decision making to the operator, providing appropriate man-machine interfaces to facilitate this function. Automation of high level functions does not seem presently possible. Within this framework, automated subroutines are feasible to improve system performance and reduce operator workload during the root pass, the fill passes, and the capping passes. Following the literature survey, it is concluded that it is probably feasible to build a system which incorporates the following functions:

- seam tracking (all passes)
- adaptive control of welding parameters to compensate for external factors such as root gap (root pass only), groove area variations (fill passes), and welding position.
- direct control of weld pool size and penetration (root pass only).

- provide operator-selectable deposition routines such as full weave or split weave (fill passes).

- detect and patch areas of underfill (capping passes).

- provide the operator with high-quality visual and acoustic feedback and interactive controls (all passes).

4. Adaptive control of the welding process would be expected to result in practical benefits of: wider allowable tolerances on joint preparation and fit-up; reduced operator servicing of in-situ equipment; and fewer defects requiring repair and reinspection. Improved process controls may also make feasible higher-productivity variants of the basic GTAW process, for instance hot-wire addition or narrow-groove preparations, or the use of the pulse-GMAW process which could substantially reduce joint completion times.

5. These desirable features will require significant research, design, and development efforts to bring them to fruition. While some features might be offered in commercial equipment in the near future, it is unlikely that welding equipment suppliers on their own will undertake all the necessary effort, because of the high cost of development and limited sales prospects. Consequently, end-user utilities may have to take the initiative. Since relevant development work is continuing in many quarters, it would be beneficial to establish and maintain contacts with other research and consulting organizations, both within Canada and elsewhere, for assistance, cooperation and possibly collaboration. Organizing a program in this area through a central utility body such as CANDU Owners Group (COG) or EPRI would have the advantages of spreading the cost and opening a wider market.

## 6.0 RECOMMENDATIONS

1. It has been concluded that Ontario Hydro's pipe welding methods can likely be improved by the addition of advanced control techniques to existing mechanized welding systems. It is therefore recommended that any decisions on the value of further research in automated pipe welding be based on a good understanding of the shortcomings of conventional welding technology in the utility environment, and the consequential benefits of an advanced mechanized system. In order to enhance the value of research in welding automation, it is further recommended that any formal proposal soliciting support for work in this area be clearly structured in a modular format, giving prominence to topics which have immediate spin-off benefits to other areas while forming part of the longer range strategy for development of a pipe welding system.

2. It is recommended that conventional welding practices be subjected to study in cooperation with operating groups to better identify areas where an advanced welding system might be used to advantage.

3. Recommended topics for ongoing research which are expected to have spin-off benefits include:

   (i) Continued study of the GTAW root pass response to fit-up and positional variables to find ways in which procedures should be modified to compensate for variations in the environment.

   (ii) Pursuit of alternative procedures and processes such as high penetration/thick land GTAW procedures and the p-GMAW process which may be inherently more tolerant to fit-up and positional variations.

   (iii) Determination of suitable weld zone video techniques, which may be followed by the development of computer-aided image analysis techniques for extracting topographical information needed for seam tracking and groove fill control.

4. It is recommended that contacts with other organizations with similar interests or who are doing research in the field be explored to ascertain the possibilities for collaborative or cooperative work.

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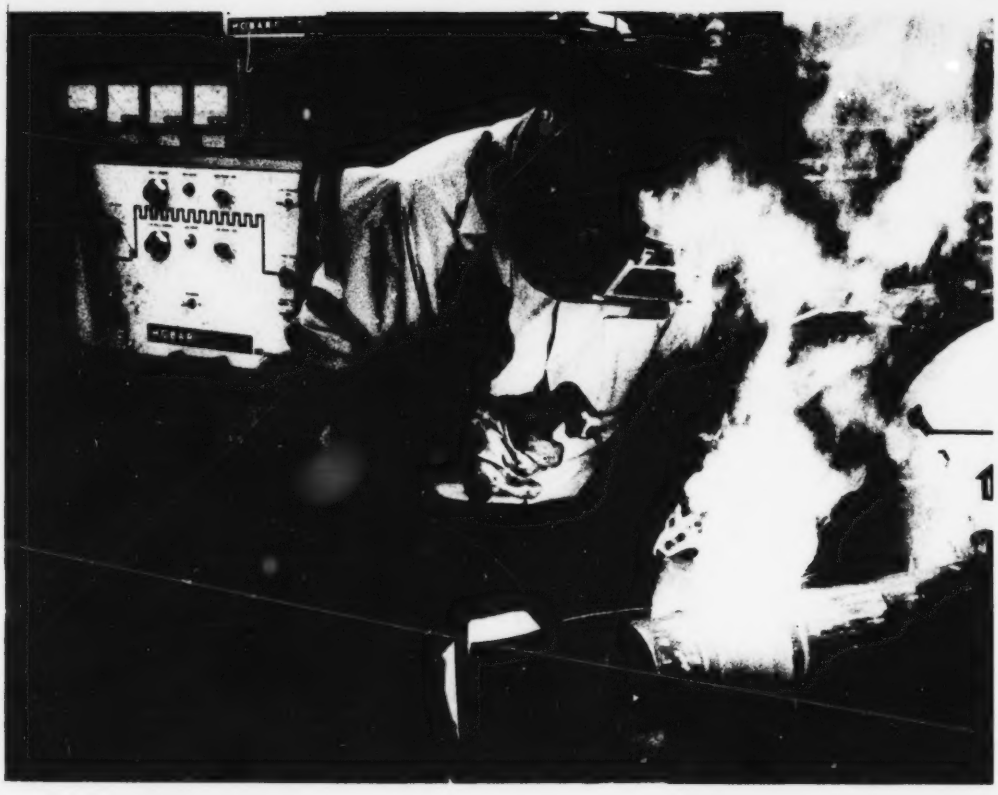


Fig 1: Manual Pipe Welding Operation

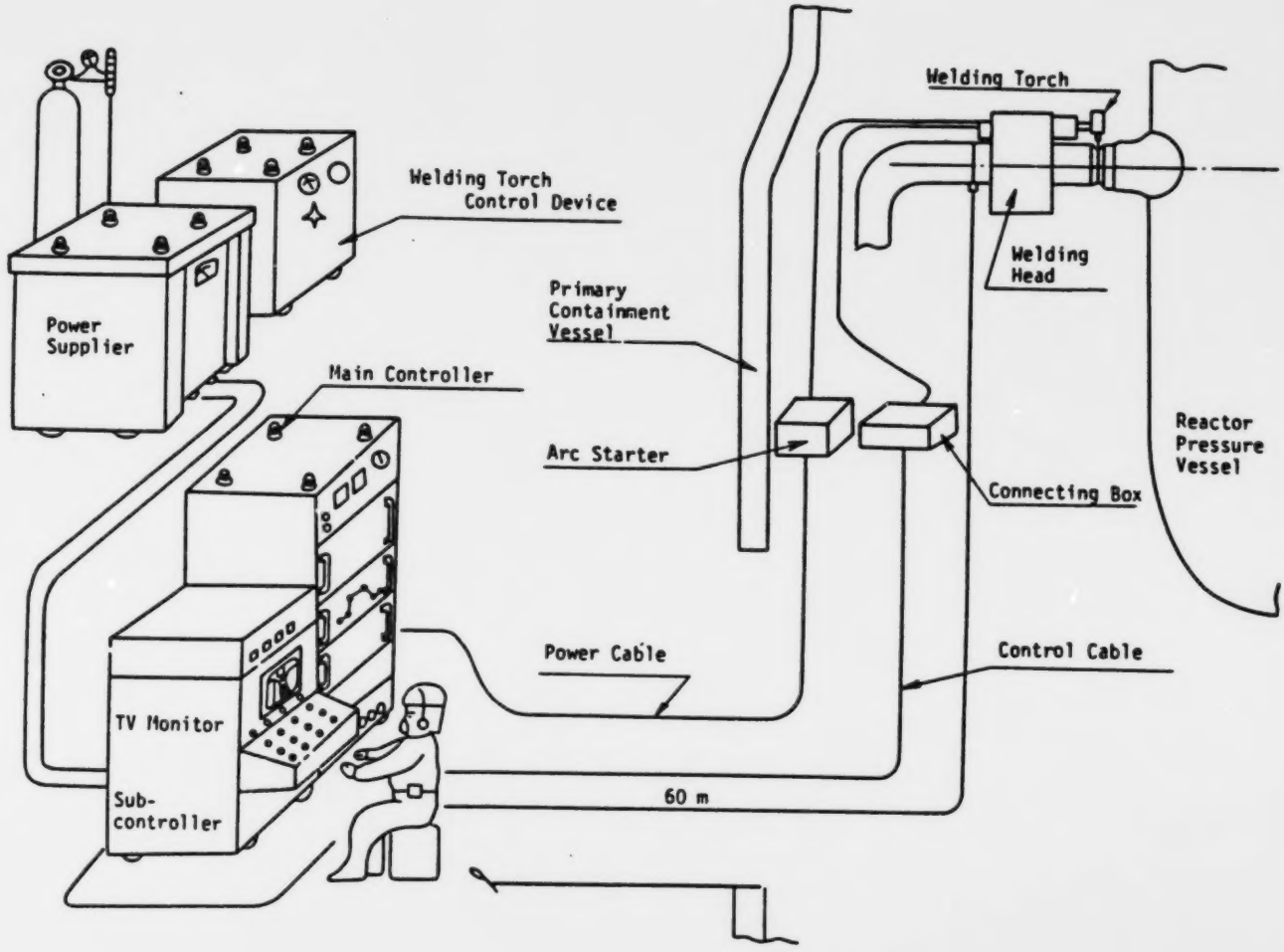
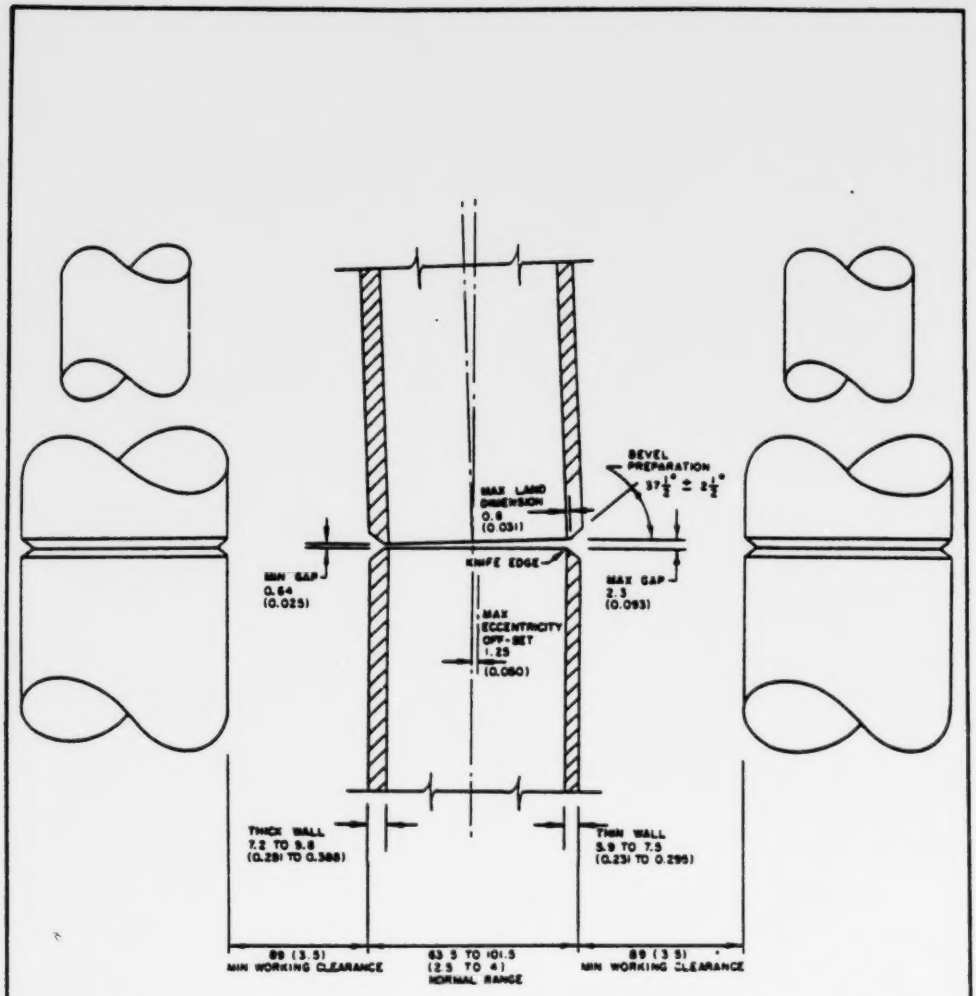



Fig 2: Schematic Illustration of Hitachi Automated Pipe Welding System For Nuclear Reactor Repair.

Source: Tamai et al.: In Electric Power Research Institute Report EPRI WS-79-174 Vol. 4, Palo Alto, 1980.




PIPE FITTING

NOTE
DIMENSIONS ARE IN MILLIMETRES AND (INCHES)

DRAWING Nº SSD753 R1

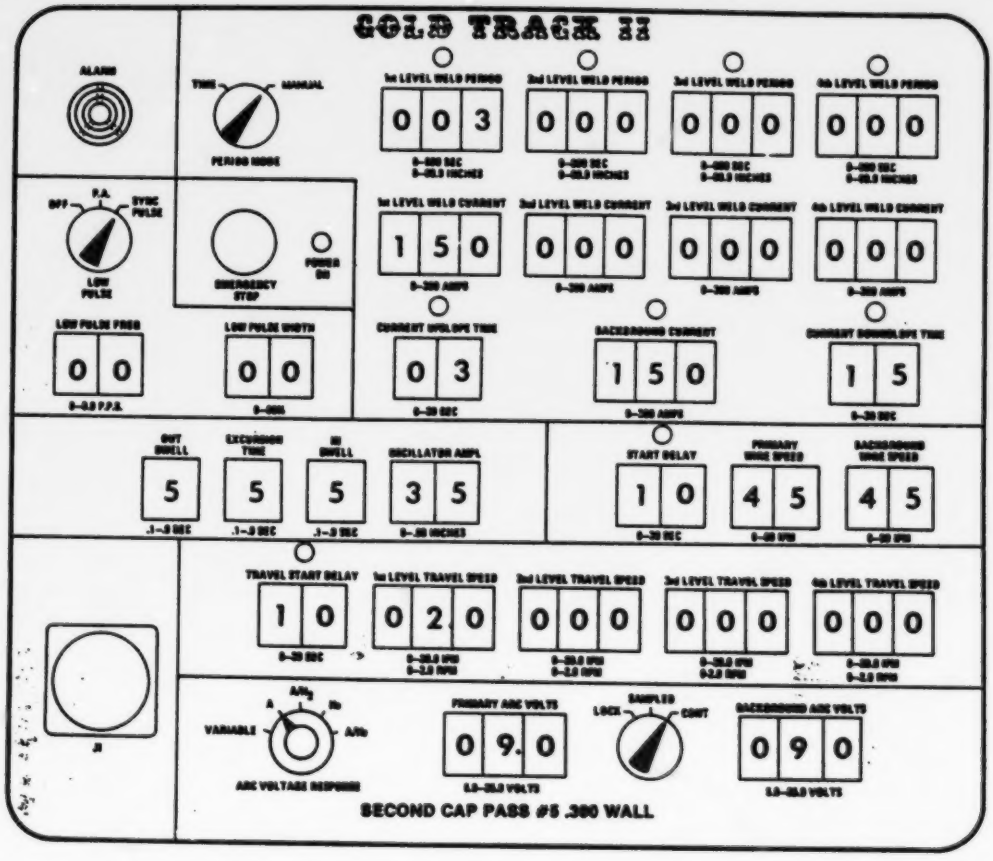
AUTOMATIC PIPE WELDER

DRAWING . . . . . 1 OF 1

FOR ONTARIO HYDRO SPECIFICATION PA02-00C-82

Fig 3: End Preparation and Fit-Up Tolerances for Automated Feeder Pipe Welding

Source: Ontario Hydro Welding Manual.



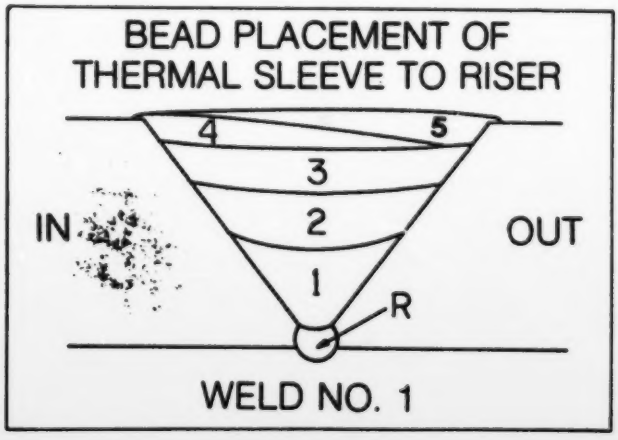




Fig 4: Illustration of Multi-Pass Pipe Weld Bead Sequence and Control Panel Set-Up for 5th Cap Pass

Source: Dimetrics Corp. product literature.

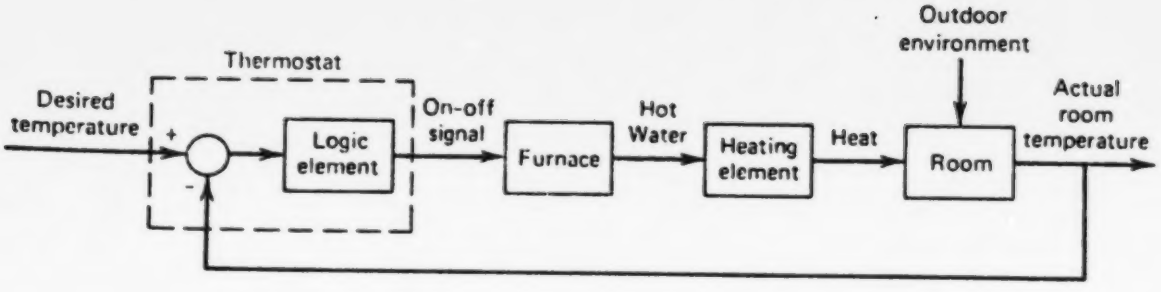



Fig 5: Block Diagram of Temperature Controller.

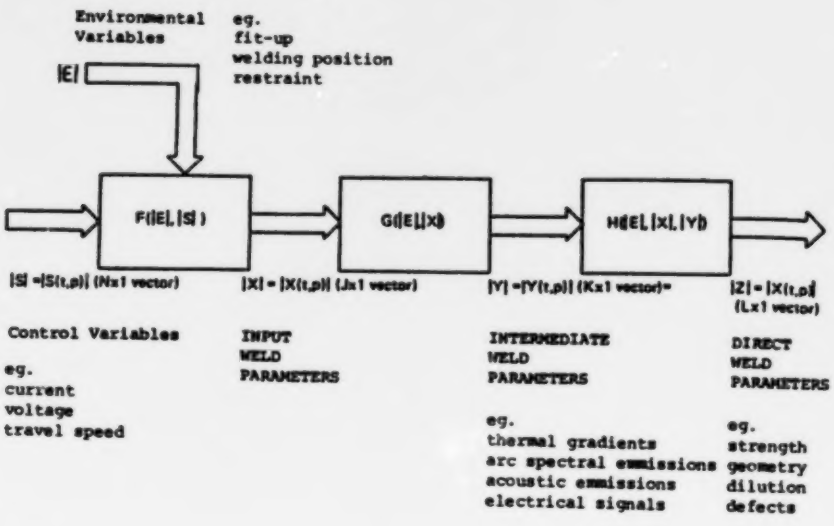



Fig 6: Block Diagram of Open-Loop Welding Process

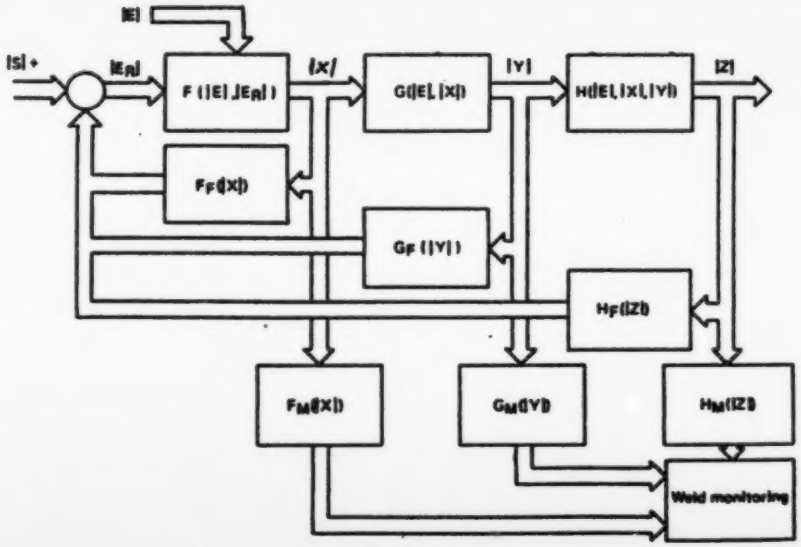



Fig 7: Block Diagram Showing Generalized Feedback and Monitoring of Welding Process Variables

Source: Cook G.E. Proceedings of The Conference on Developments in Mechanized Automated & Robotic Welding. The Welding Institute, Abington, 1980.

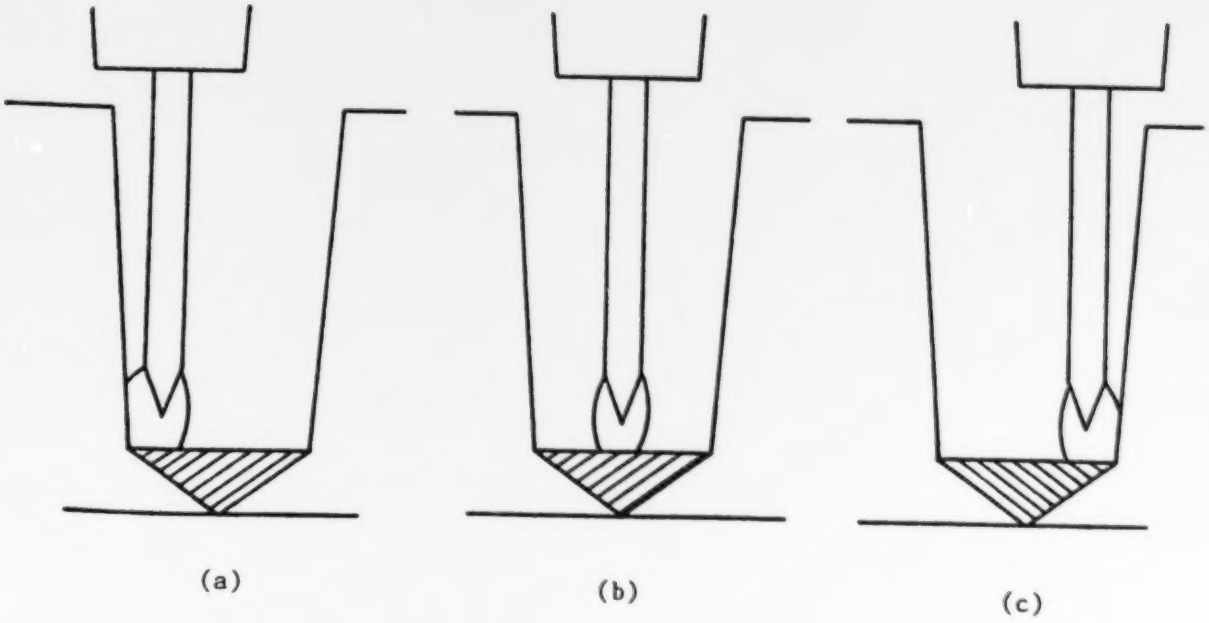



Fig 8: Through-Arc Seam Tracking System: (a) samples taken at left extreme of cross-seam excursion with AVC inactive, (b) AVC activated across width of groove, (c) samples taken for tracking at right extreme of cross-seam excursion with AVC inactive.

Source: Cook G.E. US Department of Commerce NTIS Report NSF/MEA-81004, 1981.

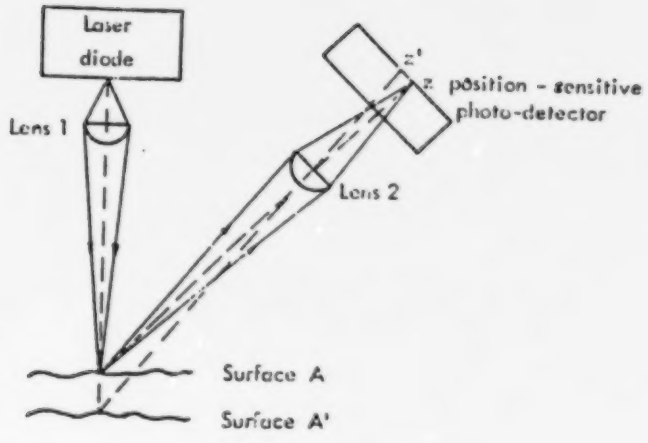



Fig 9: Illustration of The Principles of Laser Triangulation.

Source: Smati Z., et al. Proceedings of the British Industrial Robot Association 6th Annual Conference, 1980.

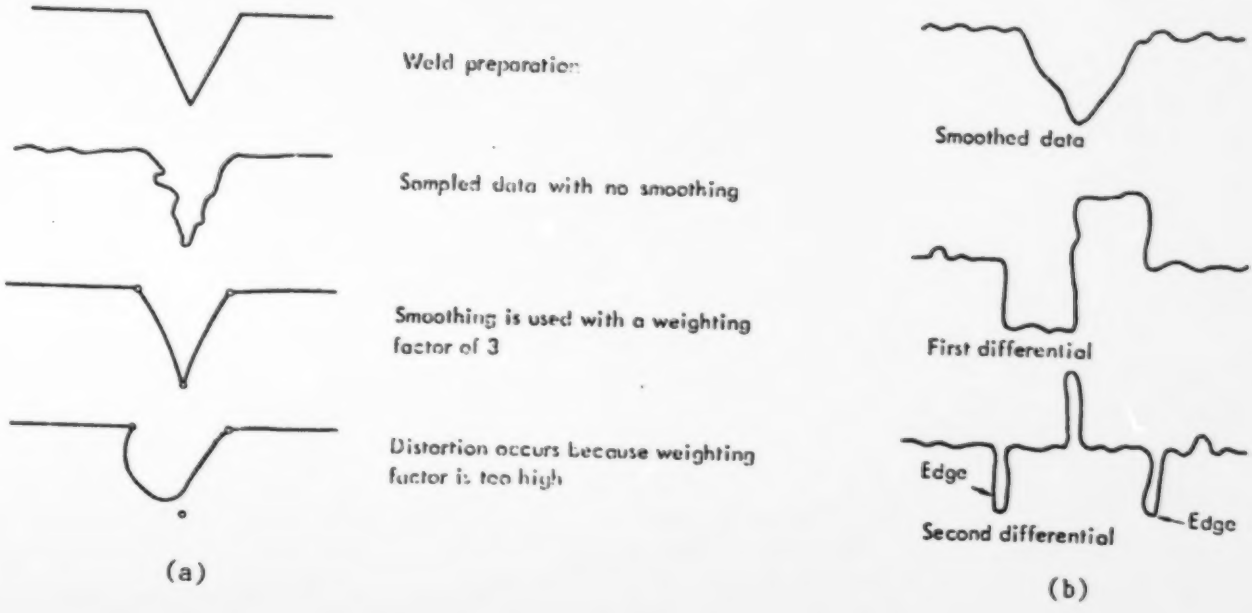



Fig 10: Illustration of Output From Laser Triangulation Device (a) With Various Degrees of Smoothing (b) Valuation of Slopes Algorithm For Detecting Groove Edges.

Source: Smati Z., et al.

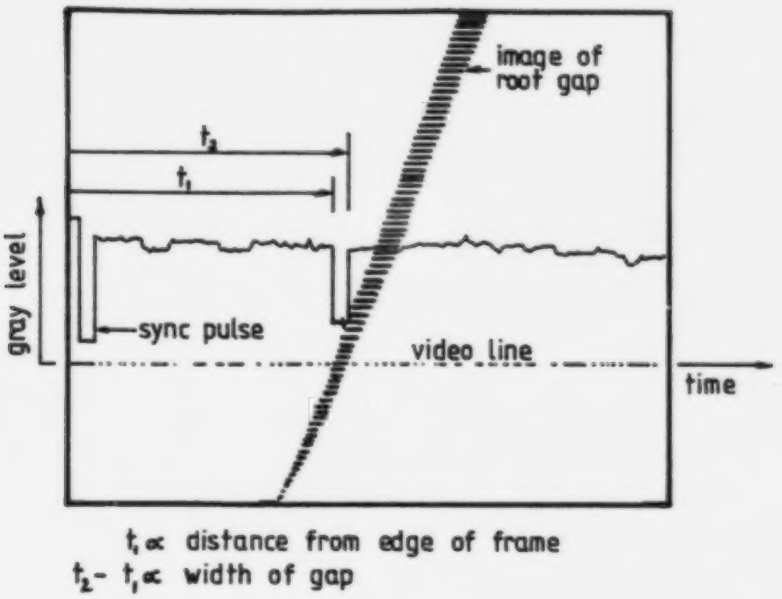



Fig 11: Illustration of Video Image Analysis Technique to Detect High-Contrast Features Such As A Root Gap.

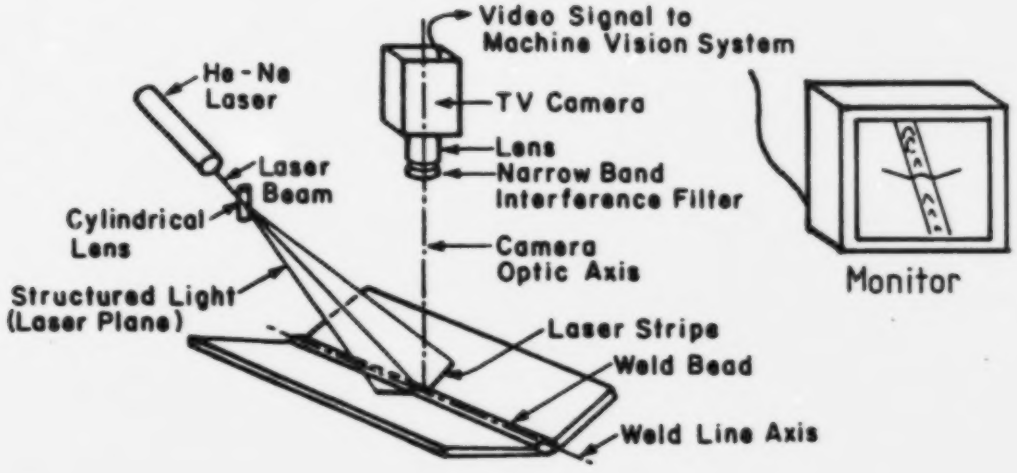



Fig 12: Light Sectioning Technique For Providing Depth Information in a Video Image

Source: Agapakis J.E. et al.: Proceedings of the Conference on Automation and Robotisation in Welding and Allied Processes, The International Institute of Welding, London, 1985.

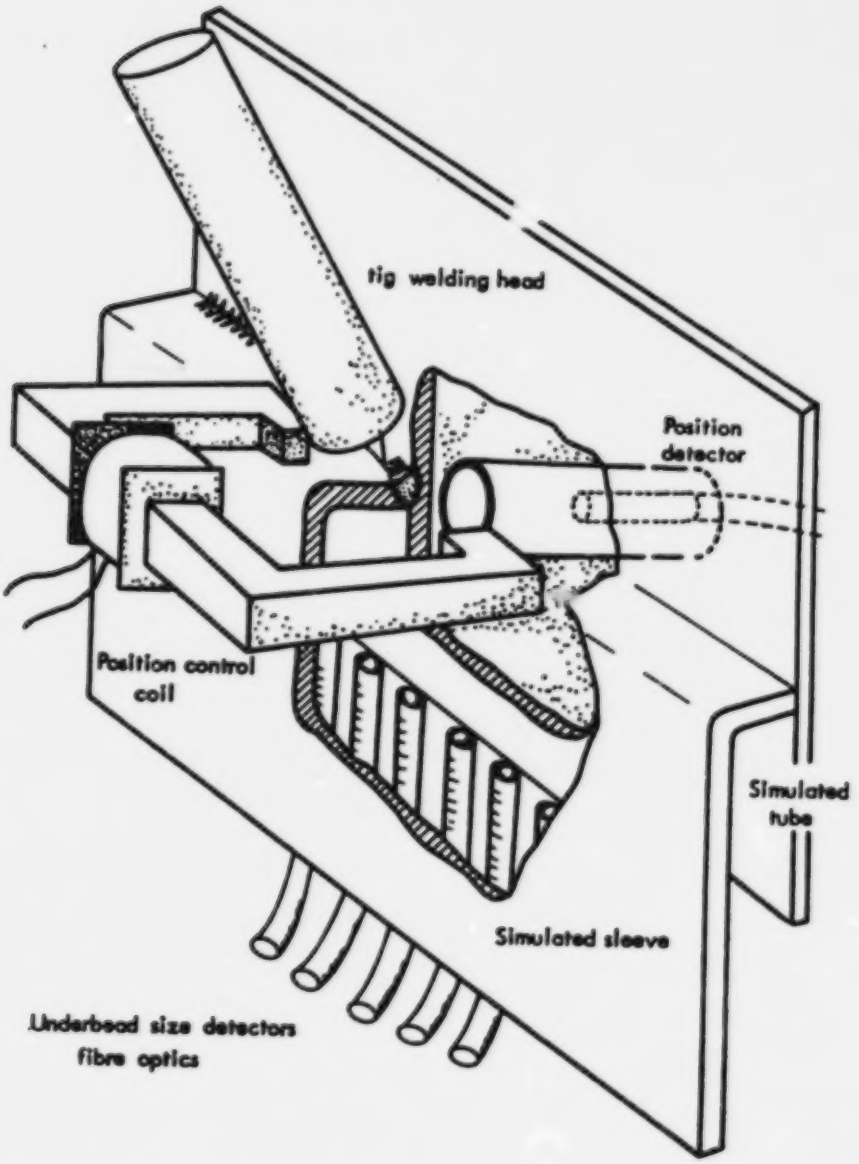
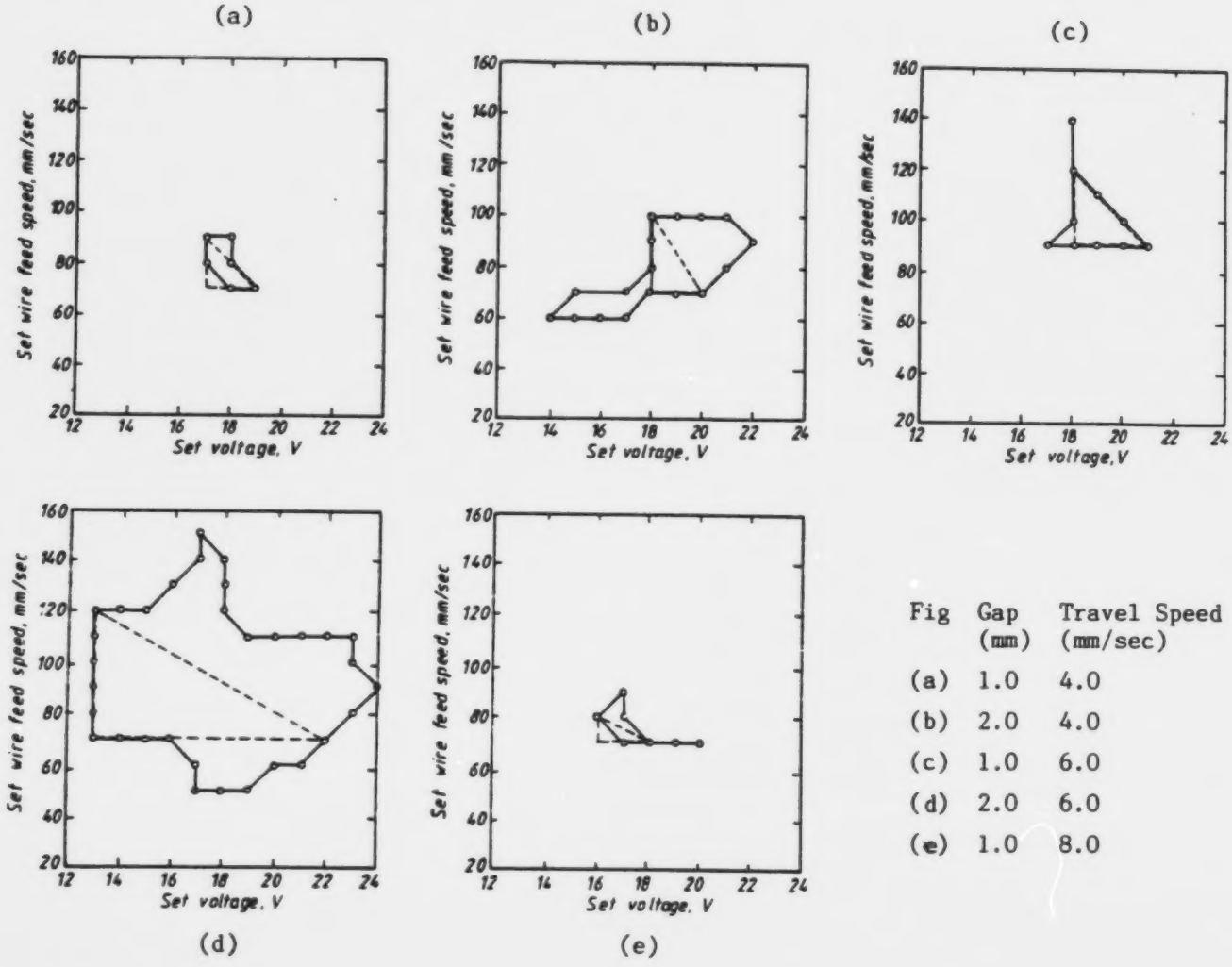



Fig 13: Diagram of Infrared Penetration Sensors for Penetration Control In a T Butt Weld.

Source: Smith, C.: Proceedings of The Conference on Welding and Fabrication in the Nuclear Industry. The British Nuclear Energy Society, London, 1979.




| Fig | Gap (mm) | Travel Speed (mm/sec) |
|---|---|---|
| (a) | 1.0 | 4.0 |
| (b) | 2.0 | 4.0 |
| (c) | 1.0 | 6.0 |
| (d) | 2.0 | 6.0 |
| (e) | 1.0 | 8.0 |

Fig 14: Tolerance Boxes For GMA Welding of Steel Sheet.

Source: Doherty J. and S.J. Holder: Welding Institute Research Members Report 211/1983. The Welding Institute, Abington, 1983.

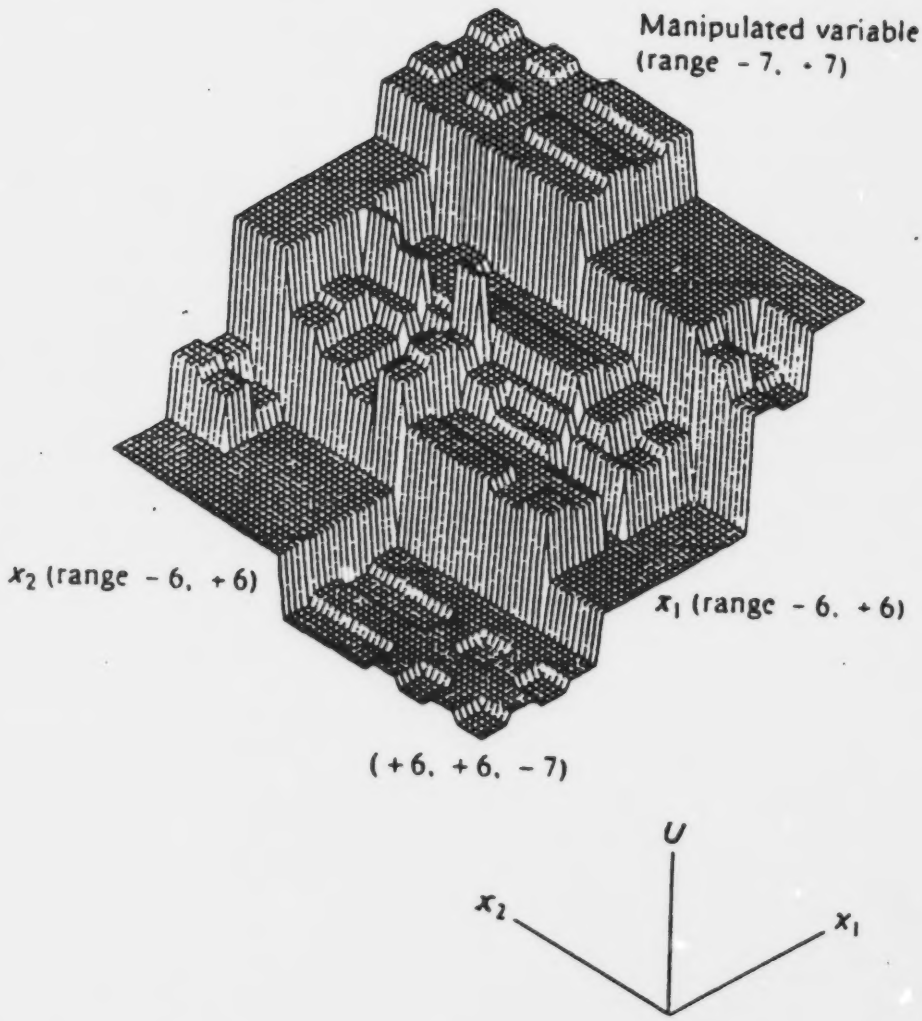
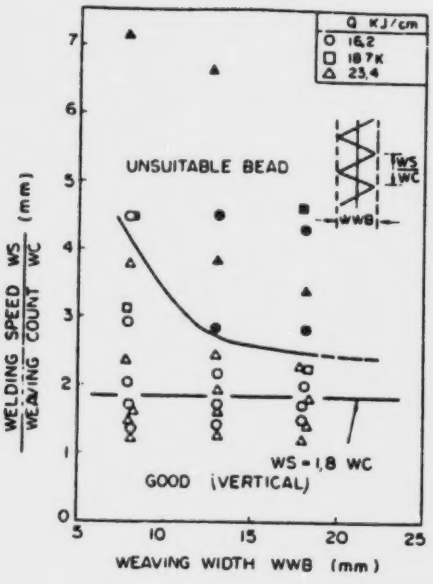
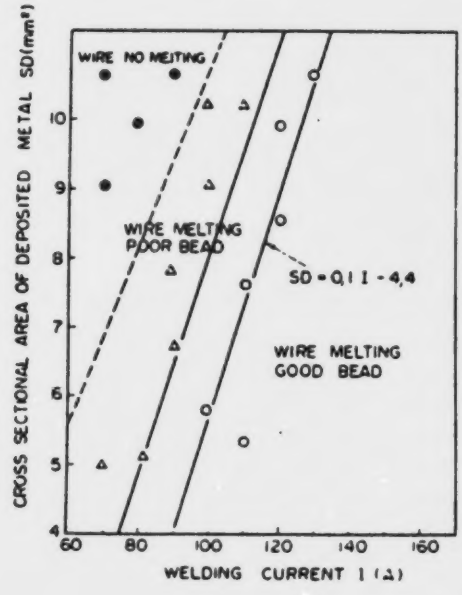
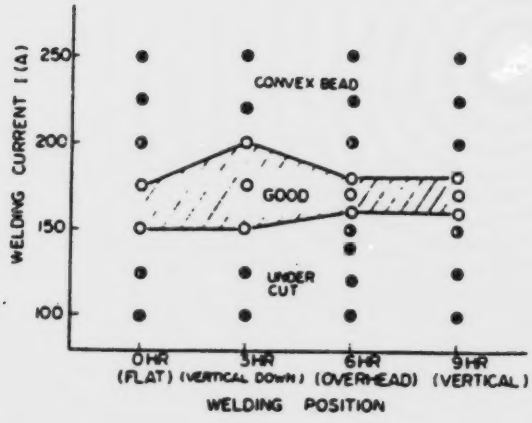



Fig 15: Graphical Model of Controller Showing Required Values of The Manipulated Variable (U) Over a Range of The Independent Variables ($X_1$ & $X_2$).

Source: Daley S. and K.F. Gill: Proc. I Mech. E. 19, 9 (1985), No. C1.





WIRE NO MELTING
WIRE MELTING POOR BEAD
SD = 0.1 I - 4.4
WIRE MELTING GOOD BEAD
CROSS SECTIONAL AREA OF DEPOSITED METAL SD(mm²)
WELDING CURRENT I (A)



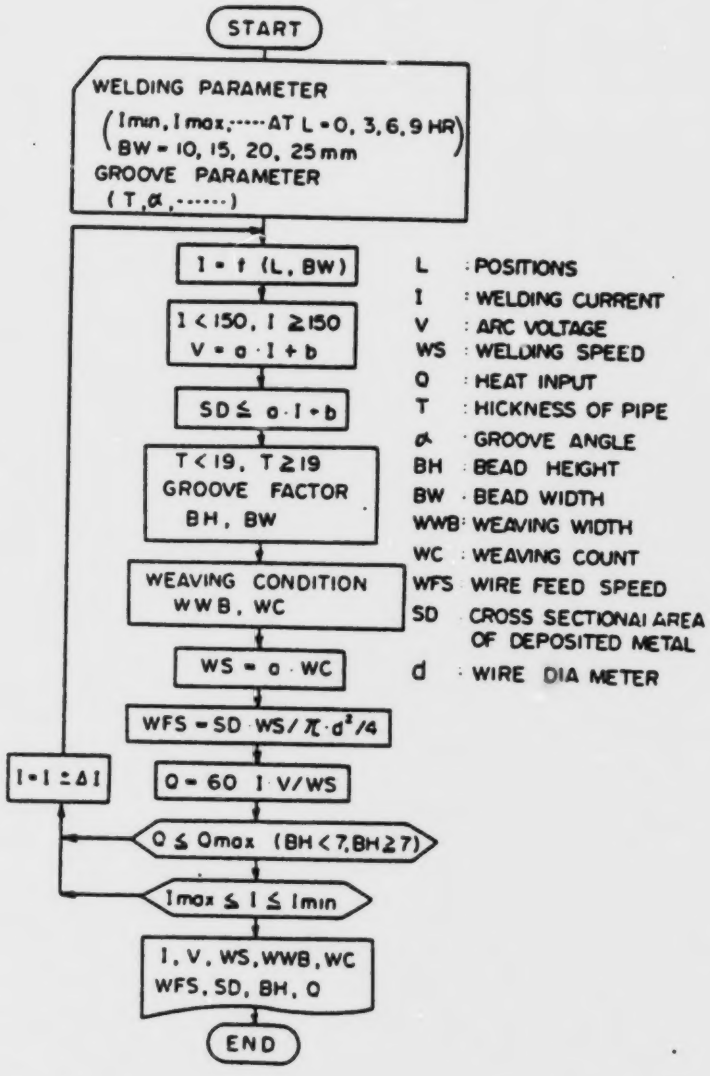


START
WELDING PARAMETER
(Imin, Imax;---- AT L = 0, 3, 6, 9 HR)
BW = 10, 15, 20, 25 mm
GROOVE PARAMETER
(T, α, ------)
I = f (L, BW)
I < 150, I ≥ 150
V = a · I + b
SD ≤ a · I + b
T < 19, T ≥ 19
GROOVE FACTOR
BH, BW
WEAVING CONDITION
WWB, WC
WS = a · WC
WFS = SD · WS / π · d²/4
I = I ± ΔI
Q = 60 I V / WS
Q ≤ Qmax (BH < 7, BH ≥ 7)
Imax ≤ I ≤ Imin
I, V, WS, WWB, WC
WFS, SD, BH, Q
END
L : POSITIONS
I : WELDING CURRENT
V : ARC VOLTAGE
WS : WELDING SPEED
Q : HEAT INPUT
T : HICKNESS OF PIPE
α : GROOVE ANGLE
BH : BEAD HEIGHT
BW : BEAD WIDTH
WWB : WEAVING WIDTH
WC : WEAVING COUNT
WFS : WIRE FEED SPEED
SD : CROSS SECTIONAL AREA OF DEPOSITED METAL
d : WIRE DIA METER

Fig 16: Algorithm for Fill-Pass Control With Supporting Experimental Relations For The Hitachi Automated Pipe Welding System.

Source: Ando S. et al.: Welding In Nuclear Engineering, DVS Berichte, 52, 1978.

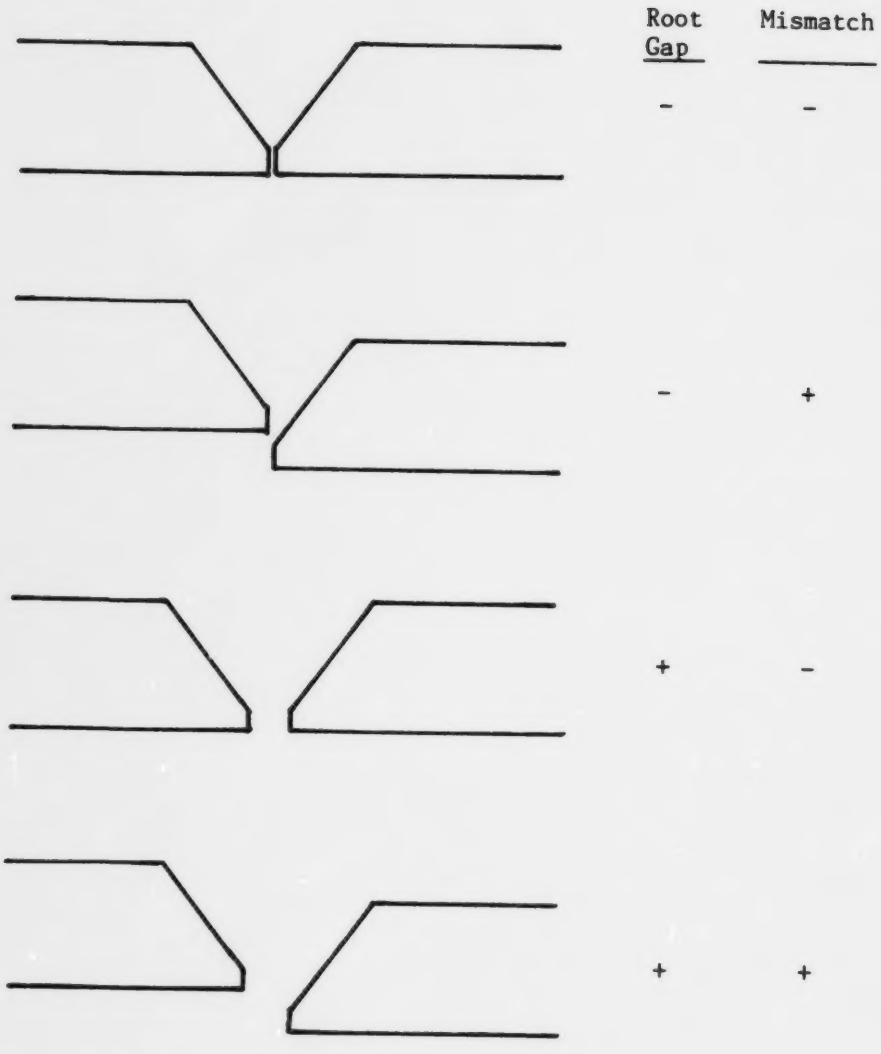



Fig 17: Illustration of Various Combinations of Root Gap and Mismatch

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# 2

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# AN ASSESSMENT OF AUTOMATED PIPE WELDING - LITERATURE SURVEY

Report No. 86-27-K
Volume 2
Appendices

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## A1.0 PIPE WELDING IN NUCLEAR PLANT REPAIR AND MAINTENANCE

Nuclear power plants contain hundreds of kilometers of piping of different sizes and materials, and piping systems are one of the more prominent sources of failures that result in plant outage. Most occurrences requiring repair involve small pipes (50 mm diameter or less). Larger, engineered piping systems tend to have lower failure rates. However if repair or modification of larger sizes are required, the sheer size and complexity tend to make up for the lower frequency of occurrence (1,2).

The bulk of the accumulated experience in repair welding of nuclear power plant pipework is from BWR plants in both the U.S. and Japan. Intergranular stress-corrosion cracking of stainless steel reactor coolant pipes has led firstly to "patch up" overlay work and eventually to replacement of affected piping systems with less susceptible material. The logistics of this task are quite staggering. Refurbishing one plant can involve the removal and replacement of about 1,000 feet of in-containment stainless pipe in sizes up to 18 inches diameter.

PWR plants also have seen a fair amount of maintenance welding of pipework, for example feedwater line repair (6) and steam generator replacement projects.

CANDU's have not been exempt. Douglas Point consumed a fair amount of effort: repair of leaking moderator lines (8), modification of the bleed cooler system, and repair of miscellaneous small lines. Pickering and Bruce GS have recently undergone retrofit of ECI system piping. The fuel channel maintenance operations currently planned or underway for Pickering and Bruce 'A' stations will involve remote welding of, if not piping, then the channel annulus bellows.

Dollars, time, and man-rem are expended during repairs such as these. It would be wrong to assume that welding is necessarily the dominant activity, however. The work may involve gaining access to the area, assembling equipment, removal of old and damaged material, preparing and fitting up new material, welding, inspection, repair of defects and reinspection. In cases where repairs must be carried out in enclosed or highly radioactive areas, simply gaining access has been the dominant problem (6,8). Nevertheless, activities directly associated with welding usually account for a significant portion of the project expenditure, especially with larger pipes.

Mechanized pipe welding techniques have been quite widely used for construction and repair/maintenance of nuclear plants (3-10) and for other tasks with similar requirements (11). Commercially available equipment (12,13) is generally based on the Gas Tungsten Arc Welding (GTAW) process. Typically, the welding torch and filler wire feed mechanism are carried by a motorized welding head, which rotates

around the joint on a track clamped to the pipe. The welding head is connected by cables to a welding power supply and control panel, on which the necessary sequence of functions to execute the procedure is preprogrammed. Procedures are generally derived from trial-and-error experimentation. Once the parameters have been set up and the equipment is in operation, the welding operator must closely supervise the process and make adjustments as necessary. For remote-controlled operation in nuclear plants, welding heads have been fitted with miniaturized TV cameras and microphones to give the distant operator some feedback from the process. Systems typical of what has been used for remote repair in nuclear plants are illustrated by Figures 1 and 2.

Mechanized welding can substantially reduce the time and radiation dosage expended on nuclear piping repairs, compared with manual pipe welding. For instance, Tamai (4) estimated that a mechanized procedure saved 60% on man-hours and radiation dosage during welding of 8 inch Schedule 80 stainless steel pipe, as detailed in Figure 3. These benefits were obtained by the use of remote control, shorter joint completion times using the mechanized equipment, and eliminating the need for weld grinding.

It has become evident, however, that existing mechanized pipe welding techniques have drawbacks which tend to impair their usefulness. The major problems stem from two facts: (i) the welding sequence is preprogrammed, and (ii) the adjustments that can be made even with an operator in close attendance, are somewhat limited.

These are characteristics of conventional mechanized welding technology generally. Most successful mechanized applications depend on one or more of the following:

(i) Precisely defined weld preparation geometry.
(ii) Good fit-up and alignment between the mating parts.
(iii) The use of the easily-controlled, but very slow, GTA welding process.
(iv) An on-site operator to closely monitor the process and override it if necessary.

It is inherently different to work around the above four limitations when welding large pipes. Rough preparations and approximate fit-up, part of normal construction, are completely unsuitable for mechanized welding (16-18). Preparation and fit-up tolerances from a typical mechanized pipe welding procedure are shown in Figure 4. The pipe ends can be prepared to close tolerances using portable lathes (5), but obtaining good fit-up is always problematical, especially when performing pipe tie-ins (final joints between pipes fixed at their other ends). Figure 5 illustrates potential fit-up variations which may arise in practice.

Further, large pipes are of necessity welded with multi-pass procedures, as illustrated for instance in Figure 2. Multi-pass welds involve tracking the joint as it is progressively filled, taking into account changes in groove cross-section with thickness, distortion, and mismatch caused by pipe diametral tolerances. Automatic arc gap controls which are common on commercial pipe welding systems correct for radial tracking errors only. The on-site operator can make some adjustment to torch position based on what he sees, but overall control is rather hit-and-miss, and is even less efficient in remote situations where feedback from the process is meagre. The low deposition rate of the GTA process is a disadvantage which is barely offset by the higher duty cycles that can be achieved by mechanization. There are higher deposition variants of the GTA process, such as hot wire (HW-GTA) (19), or narrow gap procedures (20), but these are rarely used in practice because they tend to be even more sensitive to external factors.

As stated, the major problem areas with current mechanized welding pipe methods stem from the limitations of preprogrammed, sequential process control, which result in poor tolerance to variation in external factors. It is far from definite that devising more sophisticated controllers which have more functions and programming steps (21) would do anything to resolve this, because the real problem is how to make the machine interact with the unstructured variability in the environment.

## A2.0 RECENT ADVANCES IN WELDING PROCESS CONTROL

The economic advantages of automation have led industry to install a small, but increasing number of arc welding robots and positioners, which are typically used in batch manufacture of light and medium components such as earthmover frames, truck axles, office furniture, etc. The first generation of welding robots however suffers from some of the drawbacks associated with mechanized pipe welding equipment. Welding robots are nothing more than programmable manipulators, and while they have great flexibility in the sequence of actions they can be programmed to do, once programmed for a specific sequence, they are every bit as 'dumb' as more lowly devices. The robot may be capable of accurately following a given trajectory and delivering a precise set of welding conditions, but this precision is to no avail if workpiece geometry and fit-up vary as a result of manufacturing and fixturing tolerances. It is not always cost-effective to insist on tight part tolerances to suit the welding process. Making the process capable of adaptation to variations in the workpiece is a longer-term solution, and adaptive control therefore has become a major topic for research in 'second generation' welding automation.

### A2.1 Adaptive Control of Welding Processes - Principles

Many different types of system in fact require some form of adaptive control to operate successfully under changing conditions (22). Take for example a building's heating plant, which uses a thermostat to turn the heating off or on as the temperature of the room rises and falls, as illustrated in Figure 6. Note that the thermostat is not shown as a single element because it has two functions: (i) to measure the temperature of the room and (ii) to decide whether to turn the furnace on or off. Such a system is used because variations in the outdoor environment would otherwise cause unpredictable changes in room temperature. If outside conditions such as temperature, wind and solar heating which represent the load on the system could be predicted, then we could design a heater that would operate at a predetermined rate just large enough to replace heat lost to the outside. No control system would be necessary.

Progress in adaptive control of welding has been hampered in relation to other areas perhaps by the lack of a unified theoretical approach and by a lack of understanding of the static and dynamic characteristics of the arc and weld pool (28). Welding processes are also more complex than the analogy with a simple heating plant given above, because the system output is measured directly in terms of several variables rather than one, such as bead geometry, strength and the presence of defects, and the outputs are affected by a number of input parameters (which vary from process to process). There have been relatively few attempts to describe what adaptive control should do; what the process inputs and outputs consist of, what variables should be sensed, and how the inputs should be regulated to achieve a desired output (24-29).

One of the better overviews is that of Cook (27). According to Cook, a welding process may be characterized as a multivariate feedback process with the Input Weld Parameters (IWP), Intermediate Weld Parameters (IMP) and output or Direct Weld Parameters (DWP) defined as time and position dependent vectors, eg: Figure 7.

The IWP may be further split into 'Control' and 'Environmental' variables. Control variables include welding parameters which are under the control of the operator, such as current, voltage, travel speed, wire feed speed, etc. The Environmental variables are IWP which are to some extent independent and which cannot be directly controlled. This includes factors such as joint preparation and fit-up, seam trajectory, welding position, preheat, etc.

The IMP are peak temperatures, cooling rates, acoustic emissions, arc or weld pool radiant emissions, etc. The IMP are defined separately from the input parameters because they are dependent on the IWP.

The DWP are those parameters related directly to the weld, including; weld bead geometry, hardness, strength, sidewall fusion, porosity, etc. The DWP relating to weld geometry are width, depth of penetration, cross-sectional area.

Collectively, these sensed parameters constitute a weld signature which ideally would be unique. The components of the vector weld signature may be sensed and used strictly for QC monitoring, or for real-time monitoring with manual feedback control, or implemented directly into feedback loops for automatic adaptive control, eg. Figure 8.

A2.2 Adaptive Control of Welding Processes - Techniques/Applications

Examples of adaptive control have been investigated and in some cases commercially developed at all three levels of Cook's hierarchy.

At the IWP level, feedback control is used to regulate input parameters such as current/voltage feedback for power supply control, feedback control of motor speeds, etc. This is a trivial example in the present context, however, because all it amounts to is precise maintenance of the process input parameters at preset values.

A more interesting example of feedback control at the IWP level is "Adaptive Welding Procedure Selection", so called after work at the UK Welding Institute. In this concept, adjustments are made to a control variable, such as current, to compensate for sensed changes in an environmental variable, eg. root gap.

The required values of the control variables over the range of the environmental factors can be found by experiment and by analysis of the process (Figure 9). The results, in the form of quantitative equations or qualitative 'tolerance boxes' (Figure 10), then can be interpreted to provide the basis for software control rules in an expert system type of controller. Several examples have been included in the bibliography of this technique as applied to root bead penetration control (31-33) and control of groove fill and bead placement (34-37). Figure 11 gives a schematic illustration of a decision flow chart, with supporting experimental relations, for control of groove fill in a pipe welding system developed by Hitachi.

The next level of feedback control in Cook's hierarchy is the IMP. Using the IMP as feedback signals to regulate the process depends on finding useful physical phenomena that can be exploited. It is important that a good correlation be proved to exist between the IMP and the DWP that is is desired to regulate, otherwise there is a possibility of decision error, as illustrated schematically in the Venn diagram of Figure 12. Finding and proving such relationships is a subject for basic welding research.

Many ideas in the IMP category have been investigated at a research level. These include (see bibliography); sensing acoustic emissions from the weld to monitor for defects; using weld pool surface deflection to estimate the point of penetration melt-through as shown in Figure 13 (28); using weld pool oscillation characteristics to estimate pool size and shape (76); monitoring arc special emissions and plasma composition (77), and more. Probably the most successful concepts to date have been exploiting arc-length/arc-voltage relationships for torch guidance control, both height and cross-seam as illustrated in Figure 14 (41-46), and the use of photodetectors to sense infrared emissions from the weld pool for penetration control, for instance Figure 15 (48-52).

The final level of weld parameters available for feedback control is the DWP. Many of the DWP, such as weld hardness and tensile strength are difficult if not impossible to control directly. This is why so much research effort and ingenuity has been expended on trying to find intermediate parameters which correlate with the DWP. The most promising area is weld geometry control. There have been several studies of weld pool size control using various optical means of measuring weld width such as line-scan cameras and conventional TV cameras, regulating current and travel speed accordingly (54, 55, 61). Some of the experimental systems as-built exhibited problems with stability and convergence, eg Figure 16, but the promise is there. The rather imaginative approach of measuring weld pool size and location directly using ultrasonics has also been investigated recently by workers at MIT and in the UK (74, 75). The preliminary results are encouraging, although significant technical problems remain.

## A2.3 Sensing Devices

This section provides a review of some commercially available sensor types. See also the bibliography.

### A2.3.1 Through-the-Arc Sensor Systems

This system utilizes electrical signals from the arc for both adaptive seam tracking and process controls (41-46). CRC's orbital welding systems employ through-the-arc sensors for both GTA and GMA welding. The Cincinnati Milacron and Cloos robots utilize these sensor systems for GMA welding only. The CRC orbital welding systems have been widely used for pipeline construction. The Cincinnati system has also been used for fabrication of multi-pass boiler nozzle welds. However these orbital and robotic welding systems have not been used commercially for welding nuclear pipes. In the CRC systems, welding procedures have to be coded into the EPROM chips by the CRC technical staff, to enable the system computer to calculate automatically the weld metal required to maintain a constant volume fill and sound weld quality. These procedures are generally supplied by the users. For welding nuclear pipes, it is therefore necessary to identify suitable welding process/procedures that provide sound weld metal toughness and satisfactory root bead profile. The sensitivity of through-the-arc sensor devices to weld joints having significant geometric variations (eg. angle of side wall, high/low offset at the weld root) must be determined. In welding large diameter thick-walled pipes, a large weaving width (1") is required. Weld tests must be carried out to determine the maximum allowable weaving width according to the weld metal properties acquired.

### A2.3.2 Electro-Optic Sensor Systems

Many electro-optic sensor systems for sensing workpiece topography are commercially available or are in the development stage. These systems generally fall into one of two categories: video image analysis, and laser range finding techniques.

Video image analysis is really a group of techniques that allow surface topographical information to be deducted from a video image of the weld zone. The most basic technique uses changes in the video gray level of a video frame line to estimate the position and size of a high contrast feature within the field of view, such as a root gap, as illustrated in Figure 17 (31,59,61). An electro-optic sensor system is under development for GTA welding of shuttle main engine components at NASA Marshall Space Flight Center. The weld joint, weld pool and completed weld bead are viewed through the torch using the coaxial method originally developed at Ohio State University (61). The image data concerning the weld groove geometry and weld pool/weld bead width are processed for seam tracking and process controls. However, this system is still only applicable to single-pass weld joints.

A way of furnishing depth information in a video image is to project a sheet of bright light at an angle to the workpiece. The intersection of the light and the surface when viewed from another angle represents a cross-section of the surface, which may be detected automatically using contrast-difference techniques, and the true surface profile can then be computed using triangulation methods. The principles of this technique, which is known as "structured light" or "light sectioning", are illustrated in Figure 18 (56-60,63). State of the art systems, such as that offered by Automatix of Billerica, MA, can resolve minor features of the welded surface such as the wetting points between the weld deposit and the groove sidewalls (63). The availability of such data permits high-level control functions such as seam tracking, and monitoring of bead placement and groove fill.

In laser triangulation techniques, a narrow beam of light emitted from a laser diode is scanned across the workpiece surface and reflected light is focussed upon a detector (Figure 19). After processing the returned signals, the edges and apex of a V groove can be accurately located (Figure 20), and the availability of this surface profile data again enables high-level control functions such as seam tracking, and monitoring of bead placement and groove fill (35,36,69,71).

Two sensor systems were developed at IMRI of NRCC (M. Rioux and M. Dufour). It has been demonstrated that both systems can be potentially used for multi-pass welding applications. The technique developed by M. Rioux was adopted by Servo Robot Limited to develop a compact optical head for the Cloos robot (69). Currently it is only for single-pass weld joints. It is intended to improve the present sensor system for use on multi-pass weld joints. A sensor system was developed at the Hitachi Shipbuilding & Engineering Co. Ltd. for automatic all-position welding of penstocks in tunnels. In this system, manual setting of the track position is allowed under the automatic control mode. This function allows the operator to give a certain deviation from the groove centre to the torch when one layer is formed by a number of passes.

The present study shows that electro-optic sensor techniques can be potentially used for adaptive seam tracking and process controls of welding multi-pass weld joints. A great deal of effort likely will be required to define the weld and joint features that need to be sensed and to develop appropriate control algorithms in order to build needs-oriented electro-optic sensors for welding of nuclear pipes.

### A2.3.3 Video Viewing Systems

Closed-circuit television systems are widely used for remote-controlled welding in radioactive environments and underwater (64-67). In both oblique viewing systems (Dimetrics, Magnatech, Machida) and coaxial viewing, the welding arc (excluding coaxial viewing), the weld pool and joint area are observed by the welding operator on the television monitor, who adjusts the torch position and welding parameters to ensure satisfactory welds. The effectiveness of control depends mainly on two factors: the clearness of the image produced by the viewing system and the ability of the welding operator to interpret it.

For all-position pipe welding, parameters such as the welding current are normally changed to accommodate changes of the gravity effect and joint fit-up. The welding arc light intensity varies with the electrical current. It is therefore necessary to adjust the brightness of the image of the weld pool and joint area by changing the iris opening of the imaging lens and filters in the optical path. In currently available systems these changes are made manually, but automatic controls may be necessary. All the video cameras used in these viewing systems are required to have a wide dynamic range that is capable of resolving details in the weld pool and the weld joint over large variation of light intensity.

In repair welding of nuclear pipes, large variations of joint fit-up, joint gap, root gap and high/low misfits are likely due to pipe-to-pipe misalignment problems. It would be very difficult for the welding operator to perform near-instantaneous monitoring and adjusting the machine variables (current, position, speed, etc.) according to the weld joint fit-up variations. It may therefore be necessary to develop an expert consultation system that guides the operator through different welding conditions (ie; welding fit-up and welding position).

## APPENDIX B: REFERENCES & BIBLIOGRAPHY

## APPENDIX B: REFERENCES AND BIBLIOGRAPHY

The following bibliography contains references and abstracts pertaining to mechanized and automated pipe welding. The listing is by no means complete, since a vast amount of information has been published on the general subject of welding automation in recent years. The collection is believed to be a reasonable sampling, however. References to products have also been included where appropriate.

In an attempt to instil some order in a chaotic field, the references have been grouped into lists under the following headings. However, many papers contain elements of several categories, especially those on adaptive process control which tend to merge theory, devices, and applications. Possibly the reader interested in one of these subjects should browse the three respective lists.

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B.1 NUCLEAR PIPING REPAIR - CONVENTIONAL MECHANIZED WELDING TECHNIQUES
B.2 ADAPTIVE WELDING PROCESS CONTROL - PRINCIPLES
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B.4 SENSING DEVICES - SCIENCE AND TECHNOLOGY
B.5 PROCESS MODELLING - THEORETICAL, NUMERICAL, EMPIRICAL

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19. Hutt, G.A., "Improving TIG Welding Productivity Using the Hot Wire Technique". Weld. Res. Bull. 26, 8 (August 1985), 260-265.

20. Anon, "Orbital Narrow Gap Pipe Welding", Metal Construction, October 1977, 464-467.

21. Cragg, P.J. and A.F. Rollin, "Developments in Computerized Welding Control". Proceedings of the Conference on Developments in Mechanized Automated and Robotic Welding. The Welding Institute, Abington, 1980. Paper 1.

B.2 REFERENCE LIST: ADAPTIVE WELDING PROCESS CONTROL - PRINCIPLES

22. Astrom, K.J., "Theory and Applications of Adaptive Control - A Survey". Automatica 19, 5 (1983), 471-486.

The paper reviews general theory and applications of adaptive control. Different approaches are discussed, with special emphasis on model reference adaptive systems and self-tuning regulators. Techniques for analyzing the stability and convergence of adaptive control systems are discussed. Many references to applications are given, including feasibility studies as well as products based on adaptive systems.

23. Daley, S. and K.F. Gill, "A Justification for the Wider use of Fuzzy Logic control Algorithms". Proc. I. Mech. E. 19, 9 (1985), No. C1.

Fuzzy logic control techniques may be applicable to plant that is difficult to model mathematically, but where a human controller copes relatively well. (- such as welding - IG). A description is given of an application of fuzzy logic control to 2-variable, single input satellite attitude control.

24. Nachev, G., B. Perkov and L. Blagoev, "Data Processing Problems for Gas Metal Arc Welder". Proceedings of the 3rd International Conference on Robotic Vision and Sensory Controls. International Society of Optical Engineering, Cambridge, MA, (1984), 291-296.

The design of a control system for an adaptive arc welding robot is discussed. The upper limits of intelligence of these robots are identified. Based on this, a decomposition of the task of controlling the robot is realized. The structure of the different levels and communication between them are explained. The basic program modules at all levels are analyzed as well as horizontal and vertical data flows.

25. Wright, R.R., "Welding Automation in Action". Proceedings of the Conference on Developments in Mechanized, Automated and Robotic Welding. The Welding Institute, Abington, (1980), Paper 13.

The paper discusses pressures to automate welding as a result of economic, social and labour market factors. Automated systems are seen as falling into two categories; controlling weld bead position (seam tracking) and controlling welding performance. Five aspects for successful automation are identified, namely; closed loop control of position and direction, feedback control of welding parameters, complete sequence control and monitoring of variable functions, specifically designed equipment, and joint preparations of a sufficient standard. An application of welding 3 mm stainless steel road tankers is described, which includes weld joint tracking, torch height controls and feedback control of penetration using an underbead sensor.

26. Vilkas, E.P., "Automation of Gas Tungsten Arc Welding Process". Weld, J. 45, 5 (May 1966), 410-466.

This author is interested in automation as a means of maintaining weld quality. He struggles with a contemporary lack of understanding of just what automation of welding means. He discusses process control philosophy and arrives at a 4-way classification of variables into facility set-up, welding machine set-up, measureable process set up, and semi-measurable process variables. A block diagram of adaptive GTA penetration control system is given. A front face "penetration monitor" (essentially torch height control) and photo-diode back face penetration control are described.

27. Cook, G.E., "Feedback and Adaptive Control of Process Variables in Arc Welding". Proceedings of the Conference on Developments in Mechanized, Automated and Robotic Welding. The Welding Institute, Abington, 1980. Paper 32.

This paper from a leading writer in the field advocates a systems approach to adaptive control of arc welding processes. A conceptual model is proposed of the arc welding process as a multivariate feedback control system with the inputs, intermediate variables, and outputs defined as time and position dependent vectors. These vectors, representing a weld signature which is hopefully unique, may be sensed and used for real time adaptive feedback control, monitoring with manual feedback, or QC monitoring only. Examples are given of HW-GTA applied to narrow gap pipe welding and nuclear steam generator repair. Processing of electrical signals from the arc and image analysis of the arc area are seen as the most promising areas for development.

28. Masubuchi, K., D.E. Hardt, M.H. Paynter and W. Unkel, "Improvement of Reliability of Welding in In-Process Sensing and Control". Proceedings of the Conference on Trends in Welding Research in the USA. American Society for Metals, Metals Park, 1982. 667-688.

The authors observe that one way to reduce the cost of critical structures is to reduce the occurrence of weld defects by developing "smart" welding machines which control quality directly. Ongoing programs at MIT to develop such machines are reviewed. Besides the lack of a unified theoretical approach to welding automation, two major difficulties are seen in implementing even rudimentary control strategies: a lack of understanding of arc welding statics and dynamics, and a lack of instrumental techniques to measure weld quality. A root pass penetration control scheme is described, in which the voltage rise caused by pocl surface deflection at the instant of burn - though is used to modulate travel speed. The results presented indicate that the experimental system works crudely, lacking stability as-built.

29. Moody, W.V., "Automatic Welding Control Using a State-Variable Model". MS Thesis, MIT, 1979.

This author sets off on the laudable, if ambitious task of developing a state-variable model for the GMAW process. He arrives at a ninth order non-linear differential equation, which "after some development" may facilitate automatic process control. The paper is long on theory, but short on results.

B.3 REFERENCE LIST: ADAPTIVE WELDING PROCESS CONTROL - TECHNIQUES/APPLICATIONS

30. Mizake, N., S. Ando and R. Tokuno, "Automation of Gas Cutting and Multipass Welding Process for Pressure Vessel Nozzles Utilizing an Industrial Robot". Hitachi Review, 30, 4 (1981). 217-222.

Automation of cutting and welding procedures for pressure vessel nozzles is difficult because of the complex saddle shape created by the intersection of two cylinders. The paper describes a specially designed robot manipulator which forms weld preparations and welds nozzles. The robot calculates and executes a cutting trajectory based on given nozzle and vessel sizes. The weld volume is calculated to find the number of passes required using the GMAW process. A predetermined bead deposition sequence is then executed. Variations in groove cross-section around the nozzle are calculated from geometrical considerations and compensated for by continuously varying torch velocity to regulate filler deposition per unit length of weld.

31. Doherty, J. and S.J. Holder, "Adaptive Welding Procedure Selection". Welding Institute Res. Bull, 23, 10 (October 1982). 313-316.

The paper discusses how a welding system can be made adaptive with respect to variations in the environment, for instance root gap. In this approach, experimentally-derived tolerances boxes are used to define acceptable combinations of input (controllable) parameters with selected environmental variables. The boundaries of the acceptable tolerance regions are reduced to approximate numerical representations. If changes in the chosen environmental variables are somehow sensed, the appropriate values of the input parameters can be selected according to the tolerance-box rules. This "fuzzy logic" method is claimed to be faster in computation than mathematical representation and less cumbersome than a large look-up table.

(The method has been demonstrated in the laboratory to compensate for gap changes in MIG welding of thin steel sheet - private communication, S.B. Jones of TWI, 1985 June 26).

32. Hunter, J.J., G.W. Bryce and J. Doherty, "On-line Control of the Arc Welding Process". Proceedings of the Conference on Developments in Mechanized, Automated and Robotic Welding. The Welding Institute, Abington, 1980. Paper 37.

MIG process input variables (travel speed, wire speed, voltage, and stick out) were varied in a factorial design and the results subjected to regression analysis to obtain relations between the input variables and fillet weld dimensions. These relations were inverted to show the input values needed to produce a given weld size. The resulting equations formed a set of control laws to compensate for changes in wire stick-out (torch height) by adjusting the other three variables.

A novel method was developed for measuring wire stick-out by inducing axial ultrasonic pulses in the filler wire. Improved control of weld penetration was reported.

33. Street, N.J., J.E. Middle, P.R. Shepherd and G. Fletcher, "Adaptive Robotic Welding of Controlled Penetration Root Welds". Proceedings of the Conference on Advanced Welding Systems, The Welding Institute, Abington, 1985. Paper 5.

A system is described for control of root pass weld penetration and soundness in one-sided butt welds using the flux-cored welding process. An empirical process model is used to determine the welding control parameters needed to compensate for various combinations of root gap and root face, which are sensed on line using a laser range finder (Optocator). The Optocator is also used for seam tracking. The computer control algorithm is outlined.

34. Kohn, M.L. et. al., "A Robotic Cell for Welding Large Aluminum Structures". Proceedings of the Conference on Advanced Welding Systems, The Welding Institute, Abington, 1985. Paper 2.

A robotic welding system for armoured vehicle turrets is described. The robot previews the joint location and measures the preparation with a laser structured light technique which, with a simple experimental relationship between travel speed and MIG weld throat, is used to control joint fill. The vision system was produced by Automatix.

35. Smati, Z., P.J. Alberry and D. Yapp, "Strategies for Automatic Multi-Pass Welding". Proceedings of the Conference on Advanced Welding Systems, The Welding Institute, Abington, 1985. Paper 22.

An experimental system is described for making multi-pass pipe welds with the pulsed-GMAW process. A laser range finder is used to survey the groove profile, from which a bead sequence is automatically planned awarding to rules formulated for the specific joint type. Welding parameters are selected automatically, on the basis of an empirical model, to adjust bead size to suit the planned sequence. The system executes the planned sequence until it is nearly complete, when the joint is re-surveyed and corrections made to bring the weld flush with the surfaces.

36. Smati, Z., C.J. Smith and D. Yapp, "An Industrial Robot Using Sensory Feedback for An Automatic Multi-Pass Welding System." Proceedings of the 6th British Robot Association Annual Conference. 91-100.

An automatic system under development for remote repair of reactor components is described. Welding under these circumstances requires adaptive control, both of torch position and of welding parameters. One of the primary needs is for three dimensional imaging of the

surfaces to be welded. This is done using a commercial scanning laser triangulation device (Optocator, by Selcom of Sweden). Algorithms for estimating a V-groove profile from smoothed data by segmentation or differentiation are described. Welding parameters and number of passes for the synergic MIG process are selected according to a parametric model and experimental data. Subsequent passes are deposited after checking the profile of the partially-filled groove.

37. Ando, S. et al, "Development of Remote Control Pipe Welding Equipment with Video Camera and Computer and Welding Procedure for Nuclear Power Plant". Welding in Nuclear Engineering, DVS Berichte, 52, 1978.

The paper describes a sophisticated machine developed for repair of 8-10 inch diameter stainless steel pipes in nuclear power plants. The computer based remote control system is of special interest, because it permits welding according to conditions calculated by an internal, adaptive algorithm. This algorithm contains rules for welding under varying conditions derived from numerous "tolerance-box" type relations. The algorithm selects appropriate values for process input parameters such as welding current, travel speed, and wire speed for the root and fill passes. A silicon vision TV camera equipped with a pinhole lens provides the operator with visual feedback which he may use to adjust the process parameters slightly. A "magnetic profilometry" device feeds information on groove shape after each pass to the control computer.

38. Burke, M.A., H.B. James and R.N. Wells, "The Robotic Arc Welding System - RAWS". Proceedings of the Conference on Advanced Welding Systems, The Welding Institute, Abington, 1985. Paper 3.

The paper outlines Westinghouse work for the US Navy on a robotic arc welding system which is supposed to become a component of an "Integrated Flexible Welding System" for manufacture of small-batch components. The system will use computer-based adaptive control strategies supplied with data from a weld pool vision system to maintain weld quality. Hard details of the control strategy are somewhat lacking, however.

39. Smith, C., "Simultaneous Control of Weld Pool Size and Position for Precision TIG Welding". Proceedings of the Conference on Welding and Fabrication in the Nuclear Industry. British Nuclear Energy Society, London, 1979. 361-368.

The shape and position of TIG welds can have significant variance, which is unwanted in precision applications. Feedback control is one way of achieving consistency in these parameters. A system is described for welding flanges to tubes in a T-butt joint without fusing into the tube bore. Two complementary feedback loops are employed in the control system. Weld penetration is controlled by viewing the back of the weld with multiple fibre optics leading to

photo-diodes, the signals from which control current and travel speed. Fusion of the tube bore is controlled by viewing the tube bore with a photo-diode, signals from which are applied to a magnetic arc deflector, which controls the position of the arc with respect to the tube. The required frequency response and stability problems are commented on. The author observes that a realistic transfer operator for the system is desirable.

40. Tomizuka, M., D. Dornfeld and M. Purcell, "Application of Microcomputers to Automatic Weld Quality Control". Trans. ASME, 102 (June 1980), 62-68.

The title of this paper is a bit of a misnomer. The paper really deals from a control engineering standpoint with adaptive seam tracking to compensate for variations in part geometry during robot welding. In this context, the addition of "preview" to a conventional PID controller is studied. Preview control reduces tracking errors at high speeds (190 in/min) but is not required at low speeds for the particular mechanism involved. (Travel speed in GTAW in orders of magnitude lower than those studied, but the concept of preview may be applicable to other variables - IG).

B.4 REFERENCE LIST: SENSING DEVICES - SCIENCE AND TECHNOLOGY

41. Cook, G.E., "Research on Adaptive Arc Tracking for Welding (Final Report)", U.S. Department of Commerce NTIS Report NSF/MEA-81004, 1981.

The objectives of this analytical and experimental work were to:

(i) Correlate electrical signals obtained from GTAW and GMAW arcs with joint geometry and path trajectory, to show how intelligence from such signals can be used to implement adaptive seam tracking.

(ii) Develop control algorithms.

The report gives a block diagram layout of a GTAW system, describes a voltage sampling timing algorithm for multiplexing the AVC and seam tracking functions, presents voltage/current data, and illustrates results with narrow-gap GTAW. Similar information is disclosed for the GMAW process also.

42. Nomura, H. et al, "The Development of Automatic Seam Tracking With Arc Sensor." Nippon Kokan Tech. Rep. Overseas, No. 37 (1983), 15-23.

Time-studies of conventional mechanized orbital pipe welding show that the welding operator spends a large proportion of his time on seam tracking. Reliable seam tracking is therefore an essential function for automated systems. A seam tracking system is described which relies on vertical displacement of the arc voltage control servo at the groove edges to signal a reversal of cross-seam oscillation. (Like Cook's system, but using torch displacement rather than arc voltage directly - IG.) The last pass, when the groove edges are indistinct, is recognized as a special case. This is dealt with by recording in dynamic memory (RAM) torch lateral position data around the pipe during the penultimate pass, then playing back the data for the last pass. The suggestion is made that processing the Y-position signal could form the basis for adaptive control of bead profile. The application of actual equipment to LNG stainless steel pipeline construction is mentioned. It was intended to make over 2000 welds with the system.

43. Eichorn, F., M. Wollner and J. Platz, "GMA Welding of Filler Passes With a New Type of Arc-Controlled Seam Tracking System. Proceedings of the Conference on Advanced Welding Systems, The Welding Institute, Abington, 1985. Paper 18.

The authors describe a Through-Arc seam tracking system for groove and fillet welds using GMAW. Of particular note is the use of electronically recorded and updated estimates of the local sidewall position which can be used to supervise torch reversal and avoid failures in the event of a missed or spurious arc voltage signal.

44. CRC Corporation - Arc Sensors

Through-the-arc sensors are used in CRC's orbital welding systems for adaptive, closed-loop feedback controls of seam tracking and welding parameters. The M-1000 model is for GMA welding and the M-1400 is for both GTA/GMA welding. In these systems, correlations of electrical signals (voltage changes for GTAW and current changes for GMAW) are obtained from the welding arc with joint geometry and weld trajectory, which are used for seam tracking and welding parametercontrols. These systems have been widely used for multi-pass orbital welds in construction of pipeline. At this time bolt-on through-the-arc sensors are not available, but will likely be in the market in one or two years.

45. Cincinnatic Milacron - Through-The-Arc Sensor System

The Milatrac seam tracking system uses a 'through-the-arc' non-contacting sensor and is available with all the Milacron robot models. As the welding torch is oscillated across the seam, the sensor measures changes in the arc's current and sends corrective information to the robot control, enabling the torch to follow the weld seam.

46. Bentley, S.E. and G.O. Beale, "Identification and Improved Control of GTAW Voltages Utilizing Digital Series Compensation." Proceedings of 19th IEEE Conference on Decision and Control (Including Symposium on Adaptive Processes), IEEE, New York, 1980. 1050-7.

The paper criticizes existing GTAW arc voltage control systems (AVC) as being too "lively", exhibiting excessive overshoot in response to step inputs and long settling times. This motivated the authors to design an improved AVC system using digital methods to identify the plant model and design a regulator with significantly improved performance. Theoretical aspects of the system are described.

47. Drouet, M.G., F. Nadeau and G. Ouellet, "Acoustical Control of the Length of a TIG Arc." (Publication unknown).

A system is described for modulating the DC welding arc current with an AC component of a known frequency to produce acoustic emissions from the arc at the same frequency. The acoustic emission amplitude is a much more sensitive indicator of arc length than is arc voltage, it is claimed. Thus it provides for more accurate regulation of arc length than conventional AVC systems.

48. Smith C.J., "Self-Adaptive Control of Penetration in a Tungsten Inert Gas Weld". Proceedings of the Conference on Advances in Welding Processes, The Welding Institute, Abington, 1974. 272-282.

The theoretical basis is described for a weld penetration control system using radiation from the underside of the weld pool at selected wavelengths as the sensory medium. Black body radiation theory and the emission characteristics of the weld zone are reviewed. Electromagnetic radiation transducers are compared. Control system circuitry is shown. Various applications are proposed. One practical problem is the need to have access with a sensor to the underside of the weld. However, the sensors can be quite small and with ingenuity this requirement may not be as restrictive as it seems.

49. Bennett, A.P. and C.J. Smith, "Improving the Consistency of Weld Penetration by Feedback Control." Proceedings of the Conference on Fabrication and Reliability of Welded Process Plant, The Welding Institute, Abington, (1976). 13-19.

These authors from CEGB Marchwood have developed a method for feedback control of TIG weld penetration. The method consists essentially of sensing, using photo-diodes, the infrared emissions from the weld pool beneath a stationary torch. When the photo-diode signal reaches a preset level, the welding current is switched off and the torch indexes forward by a fixed amount to repeat the cycle. The method works well on thin materials, but exhibits stability and control problems on thicker material (6 mm). This is because the ratio of signal (emission from the pool) to noise (emissions from the surrounding HAZ) decreases with thickness. The signal-to-noise ratio can be improved by filters which pass only shorter wavelengths (500 nm) produced by the higher temperature zones. With these enhancements, the system can be employed on 6 mm steel.

50. Lahiri, A.C. and P. Gough, "An Apparatus for Controlling Depth of Weld Penetration". UK Patent 2 018 471 A.

Discloses an apparatus consisting of a plurality of optical fibres arranged to detect radiation from the underside of the heated weld zone and so to regulate welding current or travel speed.

51. Fihey, J.L., "Regulation en Temps Reél du Soudage Automatique à l'arc Electrique", Institut de Recherche de l'Hydro Québec Report 2629, (1982).

The report describes an IR-sensitive fibre optic scanning system which detects the emission (temperature) profile across the weld zone. Singularities in emissivity permit the joint and the edges of the weld pool to be pinpointed. Thus the system may be used for seam tracking and control of weld width. If the welding arc is momentarily extinguished, the pool solidification time can be measured. A theoretical model of pool solidification then permits the estimation and control of weld penetration from these data.



## APPENDIX C: TRIP REPORT - ADVANCED WELDING SYSTEMS CONFERENCE

52. Fihey, J.L., P. Cielo, and G. Begin, "On-Line Weld Penetration Measurement Using an Infrard Sensor." Production et utilisation de l'energies, IREQ, Institut de Recherche d'Hydro-Qeubec, Varennes, Quebec.

A new approach to weld penetration monitoring in GTAW or PAW is proposed. Analytical as well as numerical calculations show that a strong correlation exists between the weld penetration and the solidification time of the weld pool. The physical origin of such a correlation is that the dissipation time of the heat of fusion is larger for a deeper molten pool. The experimental verification of the basic principle was carried out by means of a rugged and inexpensive fibre-optic sensor which probes the temperature distribution of the weld pool. A discussion is presented of the relevant parameters such as the spatial and temporal variation of the thermal gradients around the weld pool as well as the infrared emissivity of the surface.

The thermographic inspection technique for real-time weld penetration monitoring is designed only for autogeneous welding with the GTAW process. It is not applicable to welding processes requiring filler metal addition.

53. Chin, B.A., N.H. Madsen and J.S. Goodling, "Infrared Thermography for Sensing the Weld Process". Weld, J. 62, 9 (September 1983). 227s-234s.

The authors offer some musings on automated welding. Control variables such as welding current or arc manipulation may be altered to compensate for fluctuations in other, environmental factors. This requires sensors to detect the state of the process, however. Sensors are seen as falling into four categories; input sensors, intermediate sensors, direct sensors, and after-the-fact sensors. Direct sensors, which provide direct information on the melting and solidification process, are crucial. The results of experimenting with a commercial infrared imaging package (Inframetrics Corporation) are described. The camera was directed towards the back side of a TIG weld seam. Various factors such as joint geometry variation, arc position, penetration depth, etc. produced recognizable signatures on the thermal image of the plate underside. It was expected that these characteristic temperature distributions might form a basis for closed-loop process control. (The need to have a bulky camera at the back of a weld is not very practical - IG.)

54. Rider, G., "On-Line Measurement of Weld Pool Surface Size." Proceedings of the Conference on Welding and Fabrication in the Nuclear Industry. British Nuclear Energy Society, London, (1979). 351-360.

It is necessary, but nevertheless difficult, to observe the molten weld pool while welding with mechanized equipment in remote applications. This author proposes two methods of doing so. The



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**Memorandum**

File/Dossier

November 27, 1985

TO: M.J. Tinkler (OHRD)

FROM: I. Grant

SUBJECT: TRIP REPORT - ADVANCED WELDING SYSTEMS CONFERENCE AND THE WELDING INSTITUTE

The following is a report on my attendance at the 'Advanced Welding Systems Conference" in London on November 19-21 and my visit to the Welding Institute on November 22.

Accompanying this report are the conference preprints, the program, and list of delegates for your perusal.

## 1.0 ADVANCED WELDING SYSTEMS CONFERENCE

### 1.1 Overview

The conference was well attended, with about 140 delegates from Canada, the US, Europe and the United Kingdom, representing academic research, equipment suppliers, utilities and the heavy fabrication and manufacturing industries. Some 45 papers were presented in seven sessions over two and a half days. The standard of presentation was generally high.

I have summarized my notes under headings of interest to us below.

### 1.2 Strategies for Adaptive Control of Welding

Making a robot interact with the instructured variability in the process and environment is a key problem in automated/ robotic welding today. Several authors discussed elements of adaptive control strategy.

Significantly, most papers in this area concentrated on various sorts of 'model reference' systems. In the parlance of the current literature survey (1), ways were described for manipulating the welding input variables in response to sensed changes in the environment by reference to a set of rules resident in control software. These rules are generally

first technique involves the use of a linear array of photo-diodes (line-scan camera) to detect thermal radiation from the weld pool, in particular the emissivity singularities that mark the edges of the weld pool. The array is scanned electronically during an arc interruption period of about 1 ms, with a repeat rate of 10-100 Hz. Arc interruption is necessary because the photo-diodes respond to the arc light. This system was thought to be suitable for feedback control of pool size/location. The second viewing method proposed was to provide good visual feedback to the welder by TV viewing, which is made possible by the choice of suitable cameras and filters.

55. Vroman, A.R. and H. Brandt, "Feedback of GTA Welding Using Puddle Width Measurement." Weld. J. 55, 9 (September 1976). 742-749.

A method of adaptive control of weld pool size was studied experimentally. The variable sensed was weld pool width, by means of a line scan camera (a linear array of photo-diodes scanned electronically). Output from the camera was used to regulate torch travel speed and hence heat input. The experimental system exhibited poor stability and convergence, however. Oscillatory behaviour and instability were observed under some conditions. It was suggested that regulating welding current might be an alternative possibility.

56. Verdon, D.C., D. Langley and M.H. Moscardi, "Adaptive Welding Control Using Video Signal Processing." Proceedings of the Conference on Developments in Mechanized, Automated and Robotic Welding. The Welding Institute, Abington, (1980). Paper 29.

Conventional mechanized FCAW welding of joints in earth moving machinery requires an operator in attendance to make continuous adjustments to welding parameters because groove geometry varies. The authors therefore developed a computer-based adaptive system for seam tracking and control of groove fill. The detector for both functions is a "structured light" optical system. The groove position and cross-section are determined on-line by analyzing the video signal output from a commercial monochrome TV camera. The second of two passes is tracked by detecting the still-distinct preparation edge augmented by first-pass data. Groove fill is controlled by adjusting welding speed on the two passes, subject to certain process and metallurgical constraints. A limited manual override is permitted.

57. Linden, G., G. Lindskog and L. Nilsson, "A Control System Using Optical Scanning for Metal Inert Gas Welding." Proceedings of the Conference on Developments in Mechanized, Automated and Robotic Welding. The Welding Institute, Abington, (1980). Paper 17.

Variation of environmental factors such as groove position and geometry causes mechanized welding systems with fixed parameters to deliver uneven weld quality. A "structured light" system is described which detects the position, height, and width of a weld seam in thin

steel sheet. A triangular projected spot of light is detected by a photo-diode line-scan camera. The computer control system uses the data thus generated to determine suitable welding parameters (from fuzzy logic rules similar to Doherty and Holder's approach) as well as to adjust the lateral position of the welding head.

58. Masaki, I. et al, "Welding Robot with Visual Seam Tracking - Unika 80A." Proceedings of the Conference on Developments in Mechanized Automated and Robotic Welding. The Welding Institute, Abington (1980). Paper 12.

The paper describes a seam tracking system which detects deviation of a seam from a standard path. The seam detection is done off-line in a separate cycle. The system is basically a "structured light" one - the analysis of the image of a standard light template projected onto the local joint area. The image processing algorithm is somewhat different, however. Processing is done on a purpose-built high speed parallel processor which performs cross-correlation calculations between the camera data and a stored image to find the displacement that results in the optimum correlation.

59. Wall, W.A. and D.L. Stephens, "Automatic CCTV Electrode Guidance for Welding." Weld, J. 48, 9 (September 1969). 713-720.

During welding of the Saturn V booster rockets, the need was evident for a joint tracking system for butt joints with tack welds. An optical tracking system using commercial CCTV components is described which picks out the illuminated joint from the surrounding plate by means of contrast differences. Techniques for processing the video signal to detect the joint are described. Video blanking is used to cut out spurious information. The technique is applicable to straight or curved joints in large components with or without tack welds.

60. Kawahara, M. and H. Matsei, "Tracking Control System for Arc Welding Using Image Sensor." International Federation for Automatic Control, Control Science and Technology, 8th Triennial Congress, Kyoto, Japan. 2117-2122.

The authors reject conventional contact probe seam tracking methods. An accurate and widely-applicable optical seam tracking system is described. The system uses a projected light template ("structured light"), a photo-detector, and noise-reducing image processing algorithm to determine the groove shape, and position the welding head accordingly. The application to welding penstocks and other large components of a hydro scheme is outlined.

61. Richardson, R.W., D.A. Gutow, R.A. Anderson and D.F. Farson, "Co-axial Arc Weld Pool Viewing for Process Monitoring and Control." Ohio State University, Center for Welding Research Technical Report 529501-83-12, (1983).

A fibre optic bundle co-axial with the welding torch gives a plan view of the weld pool and immediate area. The general arc illumination provides enough contrast to make the root gap and weld pool visible. Superimposing stripes of He/Ne laser light on the surface ahead of the weld pool gives information on the groove profile. A simple, low-cost image processing system can analyze these components of the image and issue commands for joint tracking and weld pool size control, it is claimed.

62. Browne, M.A. J.L. Falkowski and R.A. Wainwright, "Visual Seam Tracking with High Noise Content: Learning and Fading". Proceedings of the Conference on UK Robotics Research (1984), Mechanical Engineering Publications Ltd., Bury St., Edmunds, England, (1984). 109-114.

63. Agapakis, J.E., N. Wittels and K. Masubuchi, "Automated Visual Weld Inspection for Robotic Welding Fabrication." Proceedings of the Conference on Automation and Robotization in Welding and Allied Processes (held by the International Institute of Welding), Pergamon, (1985). 151-60.

An automated weld visual inspection system is described which uses laser "structured light" illumination of the workpiece and computer analysis of the image to determine weld dimensions. The claimed resolution of the system is about 0.15 mm, and picture taking and image processing takes about 0.9 sec. Once the weld dimensions and features have been recognized, they are compared with stored values and tolerances to identify defects. The use of a computer 'expert system' to interpret the results in discussed.

64. Welch Allyn Inc. - Video Viewing System

The Video Probe 2000 is a small imaging tool for direct video viewing of external and internal surfaces. A tiny electronic sensor embedded in the movable tip of the probe transmits signals to the video processor, where the image is sent to the video monitor for display. The high-resolution colour image can be magnified and frozen for precision viewing. Remote steering control provides four-way articulation of the tip of the probe, giving a broad field of vision. The probe is highly radiation resistant and is designed for nuclear applications. The small size and wide angle viewing capability of the probe make it a very useful tool for internal surface examination through narrow openings. For remote arc viewing, a special filtering system must however be designed and built for this probe to reduce the intensity of the welding arc, allowing close examination of the joint and weld area. The filtering system would also act as a thermal barrier for the probe.

65. Dimetric Gold Track II Remote Video System

Dimetrics' video system has been used with the Gold Track II welding system for a number of years through their GAPCO construction division, both in performing overlays and replacement of entire BWR piping systems. The video system provides both leading and trailing views of the weld puddle. All pictures are in full colour and utilize auxiliary lighting at the torch when the arc is extinguished. Two compact cameras are mounted directly to the weld head. Short fibre optic bundles (18 inches long) are used to pick up and transfer the image into the TV camera. When exposed to radiation, fibre optic bundles become yellow with time until they become unusable. The present system utilizes short bundles and therefore reduces maintenance cost. The video system provides remote adjustment of iris opening which controls the amount of light entering the camera. The auxiliary lighting at the torch can also be remotely controlled.

66. Magnatech Model FS 3760 Video Arc Monitoring System

This video camera system consists of two sub-miniature cameras mounted directly on the 'D' or 'T' heads of a Magnatech welding system. One camera is positioned to view the leading edge of weld puddle and provide information on filler wire-to-tungsten electrode placement. A second camera is mounted to view the trailing edge of the weld puddle and provides information on weld puddle/sidewall fusion and weld bead solidification. The Rico cameras used are claimed to be unique in that they are specially designed to resist radiation environments and to monitor a welding arc. The response of the camera to light is non-linear and results in the ability to resolve areas of both high and low light intensity. The camera housing is both water-cooled and non-metal shielded, providing protection from electrical, magnetic and radiation interference. The cameras are also equipped with remote focussing and remote iris capabilities with a special filter to allow viewing the weld area prior or during welding. Black and white cameras are chosen in this video system in preference to colour cameras mainly because of their higher resolution.

67. Machida America Inc.

The Machida viewing systems are used for remote viewing of the entire weld area (welding arc, weld pool, weld joint and weld bead) during welding. The coaxial viewing system is specially designed for GTA welding, enabling the operator to look at the weld area through the torch. The oblique viewing system provides viewing of the weld area at the front and at the rear. The image of the weld area is picked up by an imaging lens, which is transmitted through a long fibre optic bundle (up to 50 feet long) to the camera and the television monitor. The camera is placed far away from the welding site and thus sources of electrical and thermal disturbances. The size of the viewing apparatus in the immediate vicinity of the arc is significantly

reduced. These systems also provide remote controls of iris settings of the imaging lens and remote changes of neutral density filters. The brightness of the image on the television monitor can thus be adjusted during welding according to changes of welding current and thus arc intensity.

68. R.W., Richardson, D.F. Farson, C.S. Jones and P.F. Rogers, "Vision-based Adaptive Welding System for Aerospace Application". Ohio State University, NASA Marshall Space Flight Center and Advance Robotics Corporation.

A vision based robotic welding system for the GTA welding of Space Shuttle Main Engineer components at NASA Marshall Space Flight Center in Alabama is described. The coaxial viewing method developed at Ohio State University is used in this welding system. The weld joint, weld pool and completed weld bead are viewed in a single television image. A special computer is used to analyze the image and provides an intelligent interaction with the robot. Analysis of the image is done with two parallel processors running at high speed, one analyzing the joint and the other one the weld area (for the same television image). A third processor supervises vision processing, implements control algorithms and communicates with the robot controller. A sample rate of ten times per second is achieved. At a welding speed of 10 ipm (25.4 cm/min) a correction is achieved for every 0.016 in (0.4 mm). The television image is thus processed in real time to identify the relative location of the joint, weld pool and weld bead features. The system is designed to recognize joint edges and root openings for joint tracking and control of weld pool along the joint. Current control is obtained from detection of weld pool/weld bead width. The vision system operates from a data base which is called up via command from the robot weld program. The data bases or 'weld tables' are built up using a teaching mode incorporated within the vision system. Research work is still in progress.

69. Servo Robot - Electro-optic Sensor System

The sensor system is designed for automatic control of arc welding processes and consists of a small optical head (10 cm x 10 cm x 11 cm) and a processor unit. The optical head consists of a solid state camera and two laser scanners. The three-dimensional location of joints on a scanned surface are determined utilizing synchronized scanning and optical triangulation techniques (originally developed by M. Rioux of IMRI, NRCC). It is claimed that synchronized scanning allows a very large view to be obtained without compromising resolution, a large increase in speed of measurement, and considerable reduction of optical head size. The prototype sensor system is currently interfaced with the Cloos Robot. It provides geometry parameters (position of joint edges, centreline, joint volume, gap and offset) for real time seam tracking and process controls. At this time the sensor system can only track simple V-groove butt joints

involving one or two weld passes. However, improvement of the sensor system for tracking multi-pass groove melds is in progress. Currently the sensor system is designed for GMA welding only. The sensor system is priced at approximately $50,000.

70. M. Dufour and G. Begin, "Adaptive Robotic Welding Using a Rapid Image Pre-Processor." National Research Council Canada (NRCC), Industrial Materials Research Institute (IMRI), 75 De Mortagne Boulevard, Boucherville, Quebec J4B 6Y4.

The rapid pre-processor initially developed by NRCC and Leigh Instruments Inc. as part of the visual aid system of the space shuttle arm has been adapted to perform real time seam tracking of multi-pass butt weld and other adaptive welding functions.

The weld preparation profile is first enhanced by a project laser target formed by a line and dots. A standard TV camera is used to observe the target image at an angle. Displacement and distortion of the target image on a monitor are simple functions of the preparation surface distance and shape respectively.

Using the video signal, the pre-processor computes in real time the area and first moments of the white level figure contained within four independent rectangular windows in the field of view of the camera. The shape, size and position of each window can be changed dynamically for each successive image at the standard 30 images/sec. rate, in order to track target image singularities. Visual sensing and welding are done simultaneously.

As an example, it is shown that thin sheet metal welding can be automated using a single window for seam tracking, gap width measurement and torch height estimation. Using a second window, measurement of sheet alignment and their orientation in space were also achieved. The system can be used at welding speed of up to 1 m/min. Simplicity, speed and effectiveness are the main advantages of this system.

71. Elco Robotics Ltd. - Vision Guide System (VGS)

The Elco's VGS is a highly advanced vision guidance system for arc welding robots. Interfaces are currently available for Cybotech and Unimation (Puma) robots. The sensor of the system scans the surface of the workpiece using a laser beam and the image reflected from the workpiece is processed by a signal processing computer. Information thus obtained is used for adaptive tracking of the weld seam during welding. The VGS is capable of tracking weld seams such as fillet, cap, square-grooved butt and single V-grooved butt. In addition, the system provides a continuous flow of vision data necessary for adaptive welding control; groove width, root opening, groove area, depth of groove (throat), groove gap root-face, etc. This system enables adaptive seam tracking of single-pass weld paths for welding sheet metal with thicknesses of 0.8 mm and up.

72. Robotic Vision System Inc. - Electro-Optical Sensor System

The Robo Sensor is a non-contacting electro-optical sensor system designed for various applications including automatic control of welding, grinding, inspection and automatic 3-D data acquisition for CAD/CAM. It is currently configured for mounting to the tool mounting plate of a Cincinnati Milacron T3 robot. The system consists of a solid state camera/projector module and a processor unit. The sensor utilizes structured light projection and optical triangulation techniques to determine the 3-D surface location of the points on the surface of an object scanned by the sensor. The processor unit processes the camera data into digital data. Each surface point is located with three digital words (X,Y,Z) in Robot Sensor co-ordinates. Such positioning information can be used for tracking of weld seams.

73. General Electric - MIG TRAK

The MIG TRAK low-power laser sensor is designed to be bolted on to a standard MIG torch and used with a robot. It allows a welding robot to track and weld simultaneously. It has been claimed that MIG TRAK can track up to 100 inches/minute and handle lap, fillet, butt and V-prep butt joints. MIG TRAK is used for real-time adaptive seam tracking and will compensate for part warpage during welding by adjusting the robot's path to the seam. For tracking butt joints, MIG TRAK is limited for use on relatively thin material up to 0.25 inch thick. The surfaces must be within 15° of parallel and have a maximum offset of 0.125 inch.

74. Fenn, R., "Ultrasonic Control Devices for Automated and Robotic Welding." Proceedings of the Conference on Advanced Welding Systems, The Welding Institute, Abington, (1985). Paper 15.

An experimental technique is described for measuring weld pool size and position relative to the joint using ultrasonic shear waves during submerged arc welding of steel and gas metal-arc welding of aluminum plates with machined, square butted edges.

75. Hardt, D.E. and J.M. Katz, "Ultrasonic Measurement of Weld Penetration." Weld, J., 63, 9 (September 1984). 273s-281s.

Experiments were conducted to measure ultrasonic reflections from machined hemispheres and from weld pools in long rods. The results showed good agreement with theory, and indicated the possibility of using ultrasonics to measure weld penetration.

76. Zacksenhouse, M. and D.E. Hardt, "Weld Pool Impedance Identification for Size Measurement and Control." Trans. ASME, J. Dynam. Systems Measurements and Control 105, 3 (September 1983). 1979-194.

These authors suggest that the width of the penetration bead is an indicator of weld quality. A method is proposed for measuring the bead width in real-time by measuring the natural frequency of oscillation of the weld pool when driven by a time-varying arc plasma force produced by current pulsing. The method is developed analytically and verified experimentally for stationary weld pools. A control system based on this measurement scheme is also developed and simulation results are presented.

77. Composition Controlled Sensing U-Weld Automation Inc.

The Unisen's SP-series sensors are developed for automatic arc welding of plates and thin sheets consisting of two or more grades of materials. The concentration of one chemical element within the materials must be different. Fibre optics sensors are used to continuously collect information from the gaseous phase of the arc, which contains information on the chemical composition of the liquid weld metal. Such information is quantified and used for positioning the torch along the groove.

These sensors are designed only for tracking single-pass weld joints, which must have constant joint geometry since variations of joint geometry may give tracking errors.

B.5 REFERENCE LIST: PROCESS MODELLING - THEORETICAL, NUMERICAL, EMPIRICAL

78. Shaw, C.B., "Diagnostic Studies of the GTAW Arc." Pt. I, Weld, J. 54, 2 (February 1975) 33s-44s, Pt. II 54, 3 (March 1975), 81s-86s.

The paper begins with the premise that empirical development of welding processes and procedures is costly in terms of time and money. Substantial benefits would flow from improved conceptual and qualitative understanding of welding processes. A number of diagnostic techniques are investigated, including spectrometry, extended dynamic range photography, monochromatic photography, holographic interferometry, and mathematical modelling. The author concludes that monochromatic photography and holographic interferometry have further potential as diagnostic tools.

79. Glickstein, S.S., "Basic Studies of the Arc Welding Process." Proceedings of the Conference on Trends in Welding Research, American Society for Metals, Metals Park, (1982). 3-51.

The paper offers an expert review of theoretical, numerical and experimental studies of the GTA process conducted at Westinghouse Bettis Labs and elsewhere with the objectives of:

- Determining the sensitivity of the welding arc to process parameters.
- Determining how arc properties affect the energy distributed to the weldment.
- Developing a computer model for weld heat conduction, and
- Applying temperature transients predicted by the heat model to predict metallurgical properties.

Examples of accurate computer predictions of weld thermal and mechanical cycles are given.

80. Eagar, T.W. and N.S. Tsai, "Temperature Fields Produced by Travelling Distributed Heat Sources." Weld, J. 62, 12 (December 1983). 346s-355s.

The authors observe that early analytic heat flow models using travelling point sources do not accurately predict weld pool shape and size. For instance, Christensen's dimensionless equations give general agreement with experimental results over wide ranges of heat input. However, the scatter can be as much as a factor of three. The

formulated using Green's functions and solved numerically. Using a correction factor for finite plate thickness, improved agreement is obtained between predicted and measured weld dimensions as functions of the arc distribution parameter and Christensen's operating parameter. The authors comment that a prior estimation of the distribution parameter is an outstanding problem. Also, although radiation and latent heat effects are not very important, liquid convection in the weld pool can affect weld shape.

81. Malmuth, N.D. et al, "Transient Thermal Phenomena and Weld Geometry in GTAW." Weld, J. 53, 9 (September 1974). 388s-400s.

The authors are basically concerned with how weld acceptance criteria can be met through optimization of fixture design and process operating parameters. The cost of experimental procedure development motivated a program to study fundamental relationships in weld pool formation. The effect of latent heat on pool shape was studied. Predictions from a formula using non-linear heat conduction theory and perturbation methods indicate that latent heat has an unimportant effect on penetration. However, latent heat induces drastic elongation of the pool at higher travel speeds and power levels. Arc heat transfer efficiency was measured by a novel dry calorimetric method. Weld thermal fields were also graphically determined using infrared thermography.

82. Oreper, G.M., T.W. Eagar and J. Szekely, "Convection in Arc Weld Pools." Weld, J. 62, 11 (November 1983). 307s-312s.

Quantitative treatments of convective phenomena within arc weld pools are extremely limited, although it is realized qualitatively that fluid motion may be important. The authors modelled temperature and velocity fields driven by electromagnetic and surface tension effects in weld pools of a prior postulated cross-section. According to their results, surface tension induced flow (Marangoni Convection) dominates electromagnetic forces at low currents. It was not clear from the paper, however, to what extent the assumptions about weld pool shape influenced the results.

83. Glickstein, S.S. and E. Friedman, "Weld Modelling Applications." Weld, J. 63, 9 (September 1984). 38-42.

The authors note that experimental work to understand the effects of welding variables such as current and speed on weld geometry is expensive and time consuming. The paper describes the application of Westinghouse Bettis Labs finite element methods to problems involving the effects of heat sinking and preheating on thermal cycles and weld geometry in Zircaloy. Good correlation between model predictions and

84. Friedman, E., "Thermomechanical Analysis of the Welding Process Using the Finite Element Method." Trans. ASME, J. Press. Vess. Tech., (August 1975). 206-213.

Until recently, computational difficulties prevented comprehensive modelling of the thermomechanical behaviour of materials during welding. The paper describes the development of models for temperatures, stresses and distortions resulting from the welding process. The models are implemented in finite-element formulation and applied to a longitudinal butt weld in thin sheet. Good agreement with experiment is reported.

85. Doherty, J. and T. Shinoda, "The Relationship Between Arc Welding Parameters and Weld Bead Geometry - A Literature Survey." Welding Institute Member's Report 74/1978/PE.

This Welding Institute report reconsiders some of the approaches to predicting weld bead geometry advanced during the past 40 years. There have been many such studies, ranging from the purely theoretical to pragmatic methods based on study of actual welding conditions. Many of these efforts have simply faded away, usually under the difficulties of dealing with a number of complex and interacting variables and doubts about whether the results could be usefully applied. However, the potential value of robotics applied to welding has refreshed interest in designing adaptive control systems for welding procedures. The Welding Institute's semi-empirical approach is described briefly.

86. McGlone, J.C., "Weld Bead Geometry Prediction - A Review." Metal Construction, (July 1982). 378-384.

This article from the Welding Institute reviews theoretical, qualitative and quantitative approaches to weld geometry prediction. Weld geometry can be predicted from small, but statistically acceptable experimental data bases coupled with suitable analytic techniques. This opens the possibility of using specific equations in interactive computer programs to select welding parameters, given bead geometry acceptance criteria, plate thickness, etc.

87. Harris, P. and B.L. Smith, "Factorial Techniques for Weld Quality Prediction." Metal Construction, 15, 11 (November 1983). 661-666.

The authors criticize the tolerance box technique for welding procedure selection as being costly to develop, limited to three parameters at a time, and providing no information on interdependent variables. The factorial experimental technique is claimed to be a rapid, commercially realistic way of establishing relationships between input and output variables. An example using plasma

88. Weallens, J.W. and B. Allen, "Effect of Process Variables in TIG Welding." Welding and Metal Fabrication, (May 1969). 210-213.

The authors observe a need for basic information relating weld geometry to welding parameters because of increasing mechanization of welding, for example, pipes. Relationships between bead geometry in 304 stainless and current, voltage, travel speed, and arc length are derived experimentally. A process "tolerance box" as a function of current and travel speed is deduced.

A paper directly relevant to OH automation programs was that of Smati of the CEGB. Smati considered in detail a strategy for automated bead placement in multi-pass, pulsed-MIG welding of pipes. His ideas are complementary to those on the structure of a multi-pass TIG pipe weld expressed in Reference 1. Basically, Smati uses an empirical model to predict unit bead shapes, devises logical rules for filling the weld preparation, and compensates for accumulated prediction errors by periodically surveying the weld surface with a laser range-finder.

The use of pulse-MIG by Smati was also interesting. From discussion, however, it seems that root pass penetration control is poor, and that there is a problem with intermittent lack-of-fusion defects throughout the weld. The application of back-face penetration sensors for root pass control is being considered at the CEGB laboratories.

Street also used a laser range-finding device, but this time to estimate root gap and root face thickness. These sensed data were input to a very complete parametric model of the flux-cored process to predict welding parameters for an acceptable root pass geometry. Discussion revealed however that the amount of experimental effort required to produce the model was an alarming four man years.

Kohn of Ford Motor Co's system for robotic welding of armoured vehicle turrets used a laser sectioning technique to preview joint preparation which, coupled with an experimental relationship between travel speed and MIG weld throat, is used to control joint fill. The laser vision system was produced by Automatix.

## 1.3 Sensing Devices for Automatic Welding

Intelligent process controllers require sensory input on the state of the process and environment. Most of the major sensing device types which we have previously recognized (1) were represented in the papers of different authors. (Authors: Kohn, Burke, Street, Richardson, Fenn, Smith, Eichorn, Smati, Orzagh.)

Burke and Richardson described methods of acquiring and processing video images of the weld area for seam tracking and weld pool size control. Neither author made it very clear however, exactly how a control system would use the image benchmarks to regulate the process; description of the strategy was lacking. Burke's work on robotic welding at Westinghouse Pittsburgh is being funded by the US Navy; Richardson's

Street and Smati both used laser range-finders to acquire surface profile data. Street used the familiar second-derivative technique to pick out preparation edges.

Eichorn described a GMAW through-arc system similar to the CRC device which is employed to track irregular preparations during the fill passes. The final pass is tracked by playing back data recorded from previous passes.

Fenn illustrated the use of ultrasonic shear wave probes to detect the fusion boundary and joint interface in SAW plate welding, thus enabling penetration control and seam tracking functions. This technique is being commercially developed in the UK. It could be difficult to apply to root passes in prepared joints, however, because the more complex geometry in that case would tend to cause spurious reflections.

## 1.4 Process Developments

Automated welding demands a process that is capable of control and several authors dealt with process improvements to enhance control and reduce the likelihood of defects. Of particular interest were a number of papers on variants of the MIG process. (Authors: Daggett, Ditschum, Needham, Allum, Ogosawara and Stol.)

One of the most unique ideas was the Advanced Gas Metal Arc Welding (AGMAW) process described by Stol of Alcoa Research Centre. The AGMAW process uses a power source to preheat the filler wire to any desired level, independent of arc current, before it emerges from the torch. This invention is claimed to break the fixed relationship between welding current and wire feed speed that exists in conventional MIG welding and permits independent control of heat input and deposition. This is significant because it means that some of the flexibility and ease of control for which TIG welding has long been selected may be imparted to MIG, with the advantage of higher deposition rates.

In conversation with Stol, it seems that wire heating results in improved are stability also. No adverse effects have been observed on the lower contact tip due to the passage of the heated wire: if anything, tip wear is reduced because the wire surface is softer and less abrasive.

## 1.5 Mechanized Pipe Welding

Two papers on mechanized pipe welding applications were presented (Authors: Belloni and Knagenhjelm.)

Belloni described an application of the Merrick Corp. 4-head HW GTA pipe welding system to the TRANSMED oil transmission pipeline. The system incorporate the Merrick 'through-arc' cross-section and radial torch guidance system. Welding parameters were preprogrammed, with some adaptivity for welding position. Root pass control involved simply a fixed set of parameters and careful attention to joint preparation, however.

Knagenhjelm discussed a mechanized TIG equipment for joining underwater pipelines in a hyperbaric habitat. Underwater welding shares with nuclear repair and maintenance welding an inhospitable environment and the need for reliable remote control. While the design of the top-side and underwater equipment was quite sophisticated, the welding process itself was fairly conventional with pre-programmed procedures and simple arc gap control to compensate for radial variation only.

## 2.0 VISIT TO THE WELDING INSTITUTE

I paid a brief visit to TWI on November 22 as the guest of Steve Jones, to review TWI automation programs.

I was able to visit John Doherty's laboratory and see the rig on which he has developed techniques for adaptive control of MIG welding of thin sheet, using video image analysis to detect changes in seam location and gap. His group are currently working on a more sophisticated image analysis system which, it is hoped, will be capable of detecting the more subtle features of a partly-filled multi-pass weld.

The Welding Institute also have a number of small welding robots with simple adaptive controls such as tactile or through-arc seam following. Jones commented that TWI do not see research on welding automation in general to be of much benefit because the field is so vast, and prefer to concentrate on specific applications. TWI are offering a package of reports on remote control for about $10,000, however. These reports could be obtained through AECL's Research Membership if there is any interest.

## 3.0 CONCLUSION

As a result of making this trip, we have received exposure to the leading edge of welding automation and control technology. I personnally found it extremely interesting and hope you will agree that the information I have been able to bring back represents value for money in the OH welding automation program.

Ian Grant

I. Grant
Material Engineering Dept.
SP2F3, Extension 3620 (5730)

E.G. Price - SP2F3 (3523)
P. Maak - OHRD

853852/R
GRANT

## REFERENCE

1. Grant, I.M. and P.Y.Y. Maak: "An Assessment of Automated Pipe Welding - Literature Survey" Draft Report, 1985 July.

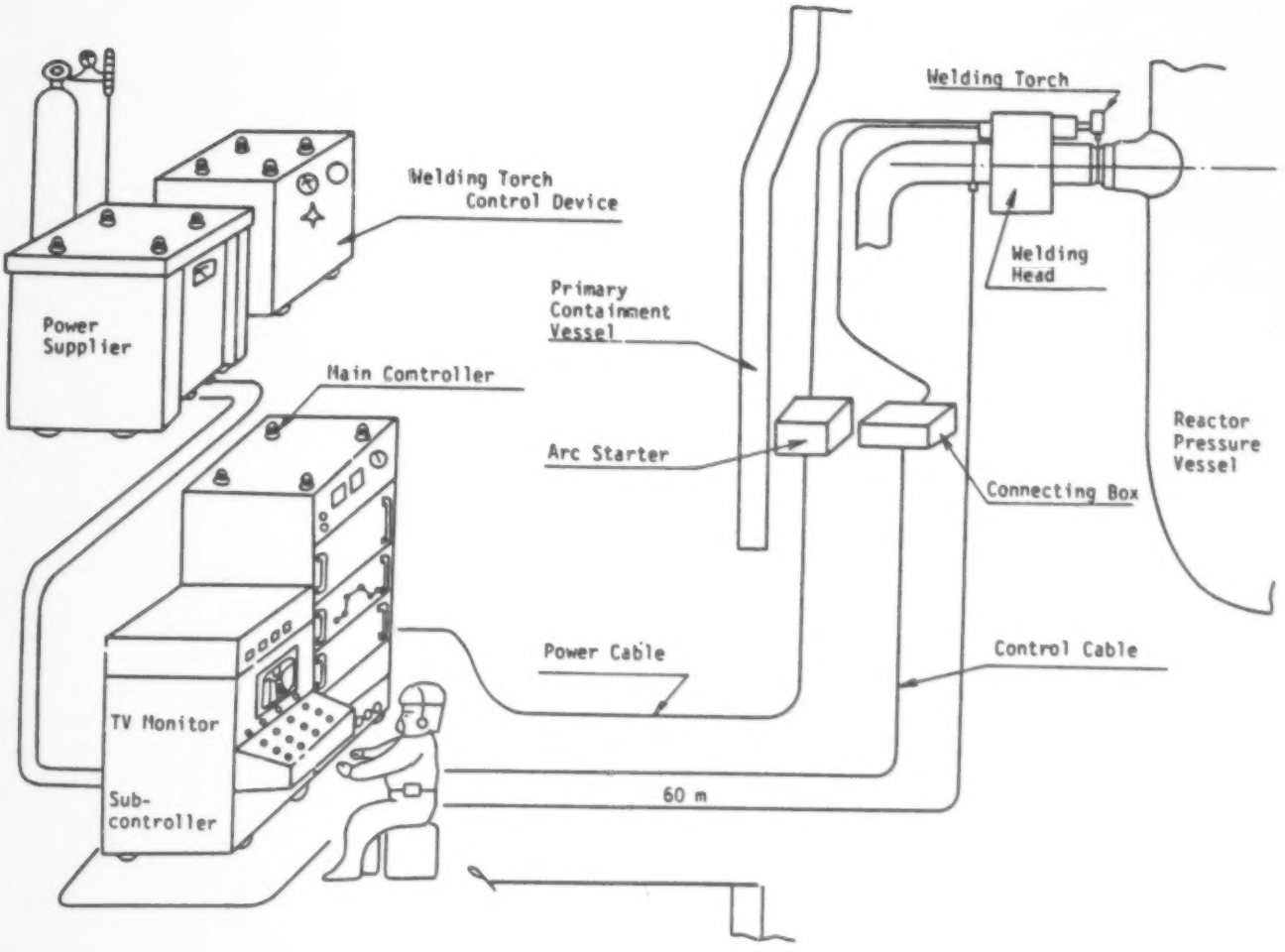
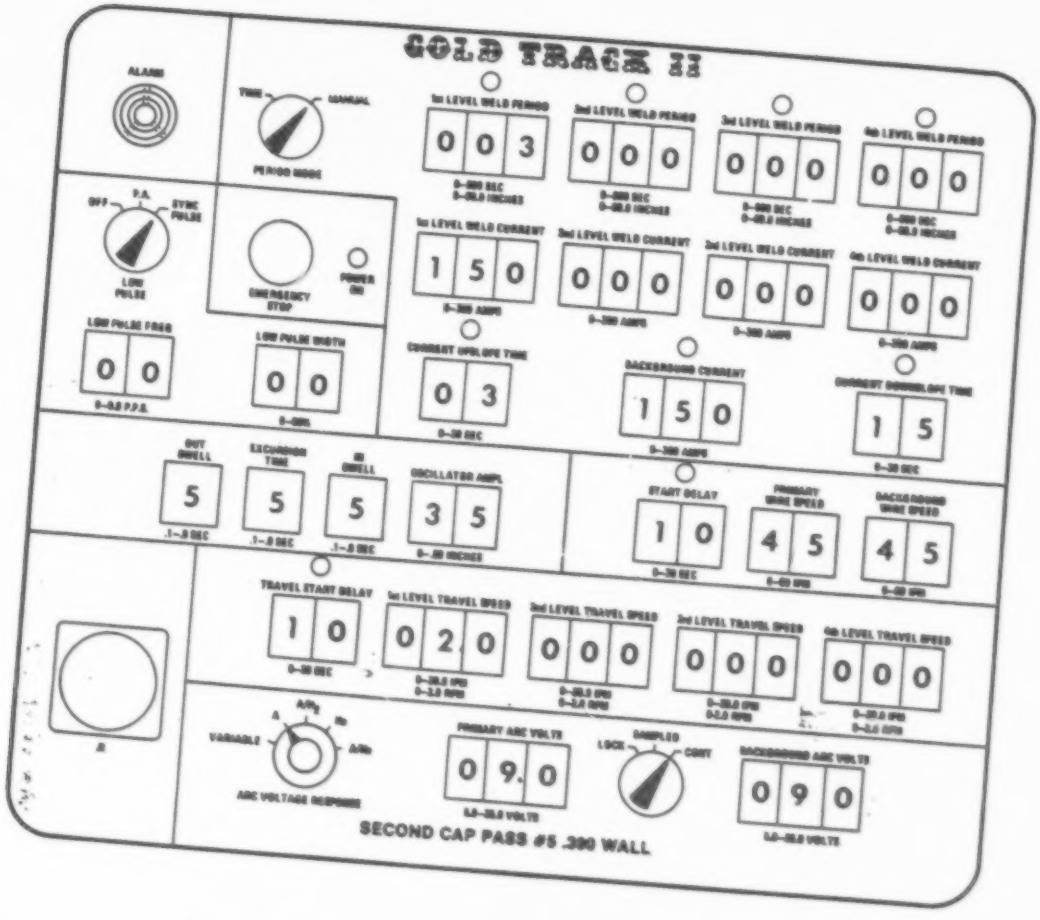
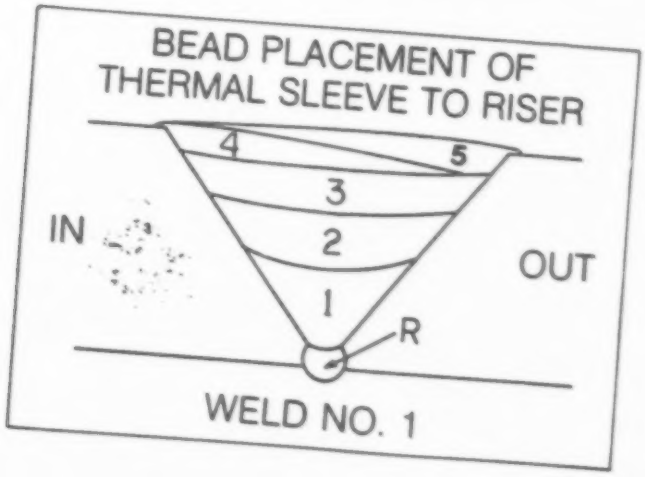


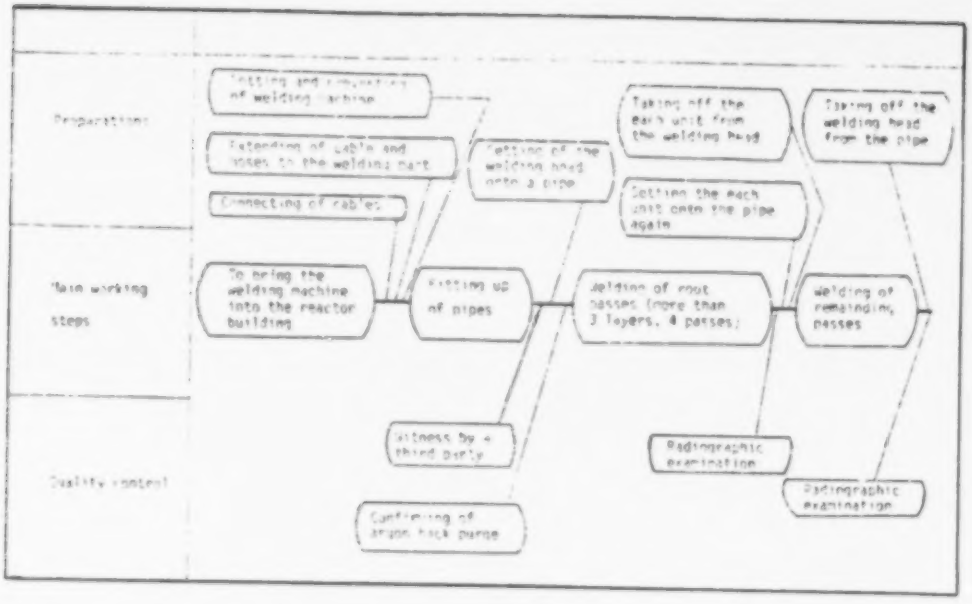

Fig 1: Schematic Illustration of Hitachi Automated Pipe Welding System For Nuclear Reactor Repair.

Source: Tamai et al.: In Electric Power Research Institute

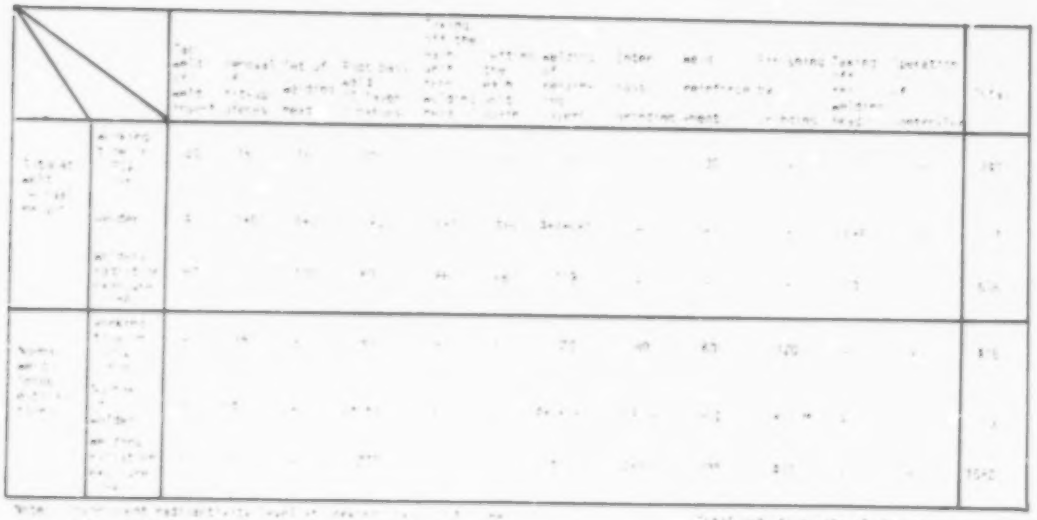

COLD TRACK II
ALARM
TIME
MANUAL
PERIOD MODE
1st LEVEL WELD PERIOD
0 0 3
2nd LEVEL WELD PERIOD
0 0 0
3rd LEVEL WELD PERIOD
0 0 0
4th LEVEL WELD PERIOD
0 0 0
OFF
P.S.
SYNC PULSE
LOW PULSE
EMERGENCY STOP
POWER ON
1st LEVEL WELD CURRENT
1 5 0
2nd LEVEL WELD CURRENT
0 0 0
3rd LEVEL WELD CURRENT
0 0 0
4th LEVEL WELD CURRENT
0 0 0
LOW PULSE FREQ
0 0
LOW PULSE WIDTH
0 0
CURRENT UPSLOPE TIME
0 3
BACKGROUND CURRENT
1 5 0
CURRENT DOWNSLOPE TIME
1 5
OUT SHELL
5
EXCURSION TIME
5
IN SHELL
5
OSCILLATOR AMPL
3 5
START DELAY
1 0
PRIMARY WIRE SPEED
4 5
BACKGROUND WIRE SPEED
4 5
TRAVEL START DELAY
1 0
1st LEVEL TRAVEL SPEED
0 2 0
2nd LEVEL TRAVEL SPEED
0 0 0
3rd LEVEL TRAVEL SPEED
0 0 0
4th LEVEL TRAVEL SPEED
0 0 0
VARIABLE
ARC VOLTAGE RESPONSE
PRIMARY ARC VOLTS
0 9.0
LOCK
DAMPED
CONT
BACKGROUND ARC VOLTS
0 9 0
SECOND CAP PASS #5 .390 WALL


BEAD PLACEMENT OF
THERMAL SLEEVE TO RISER
4
5
3
IN
2
OUT
1
R
WELD NO. 1

# APPENDIX D: FIGURES


Preparations
Main working steps
Quality control
Setting and regulating of welding machine
Extending of cable and hoses to the welding part
Connecting of cables
To bring the welding machine into the reactor building
Fitting up of pipes
Setting of the welding head onto a pipe
Taking off the each unit from the welding head
Taking off the welding head from the pipe
Setting the each unit onto the pipe again
Welding of root passes (more than 3 layers, 4 passes)
Welding of remaining passes
Witness by a third party
Confirming of argon back purge
Radiographic examination
Radiographic examination

(a)



(b)

Fig 3: (a) Operation sequence for mechanized weld and (b) comparison of welder radiation exposure in manual

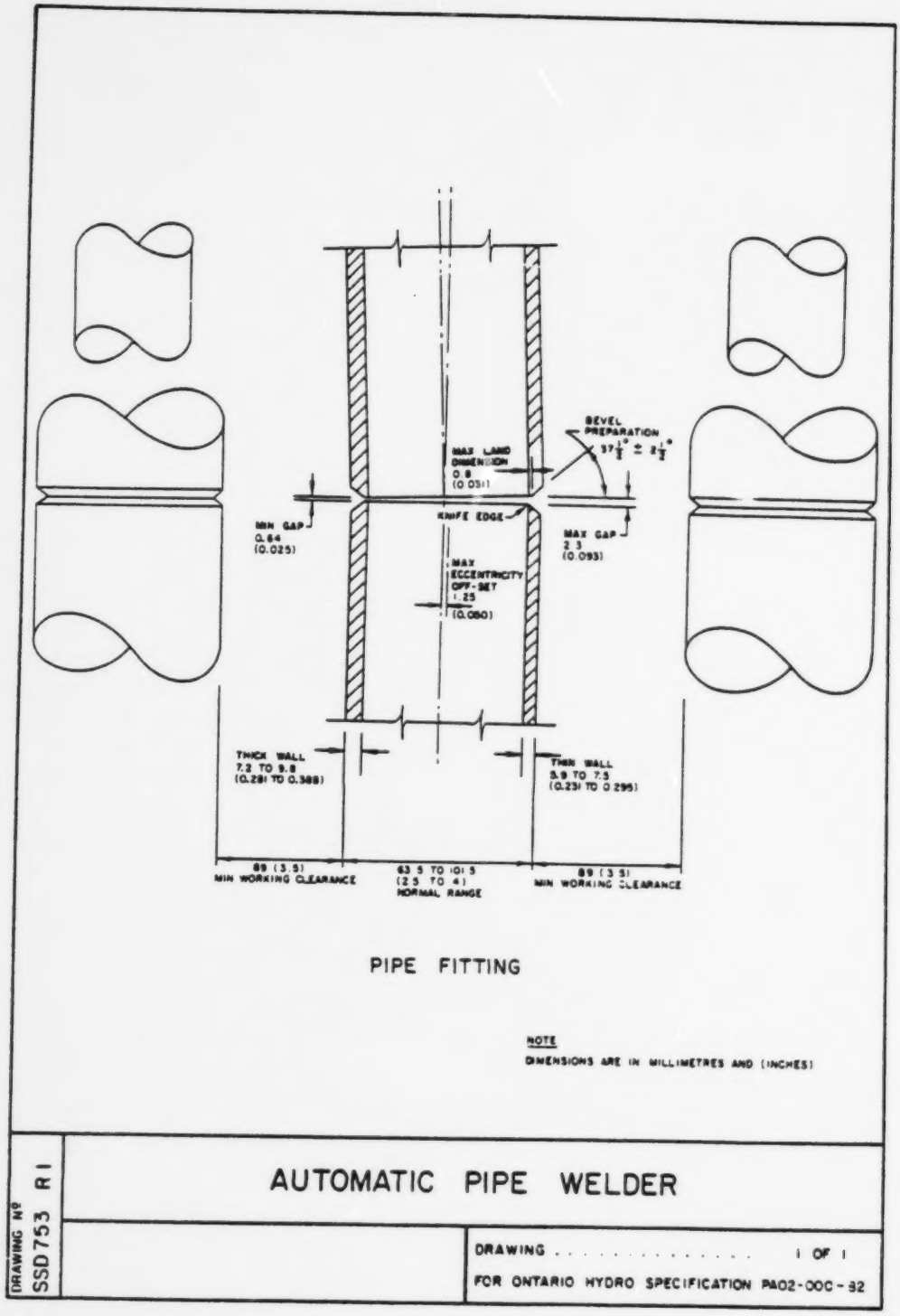



Fig 4: End Preparation and Fit-Up Tolerances for Automated Feeder Pipe Welding

Source: Ontario Hydro Welding Manual.

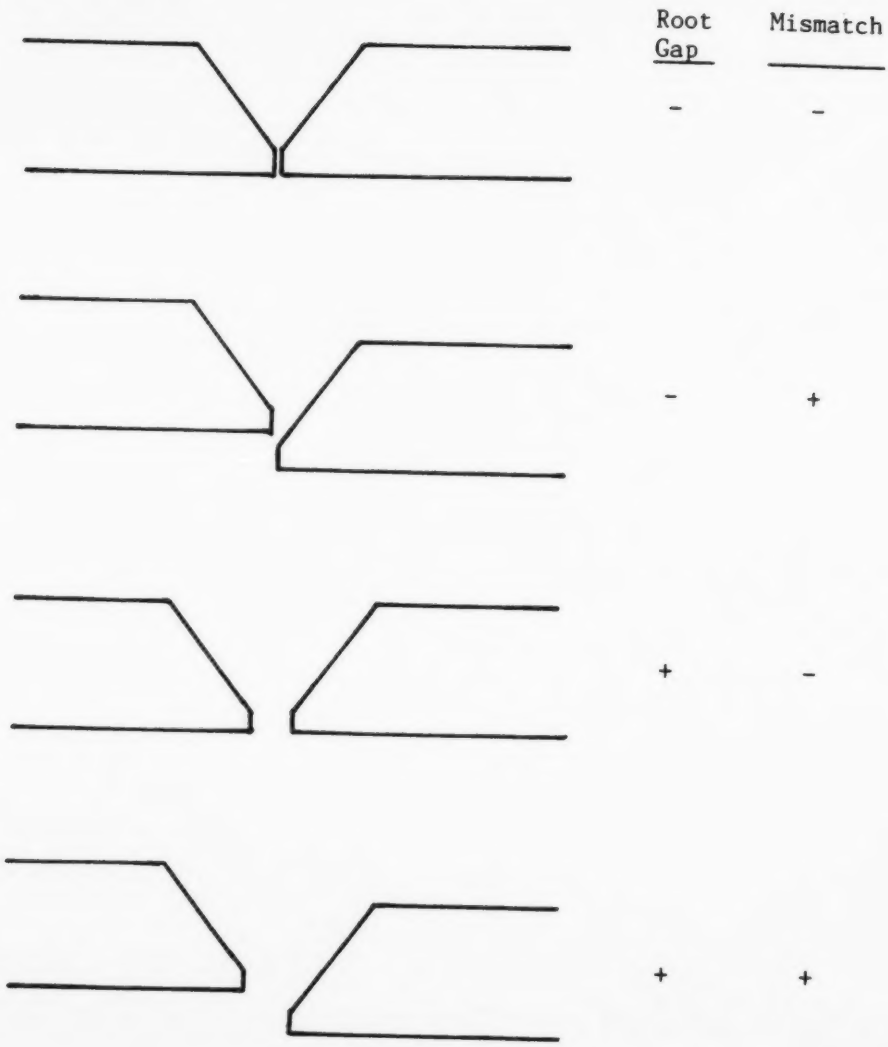



Fig 5: Illustration of Various Combinations of Root Gap and Mismatch

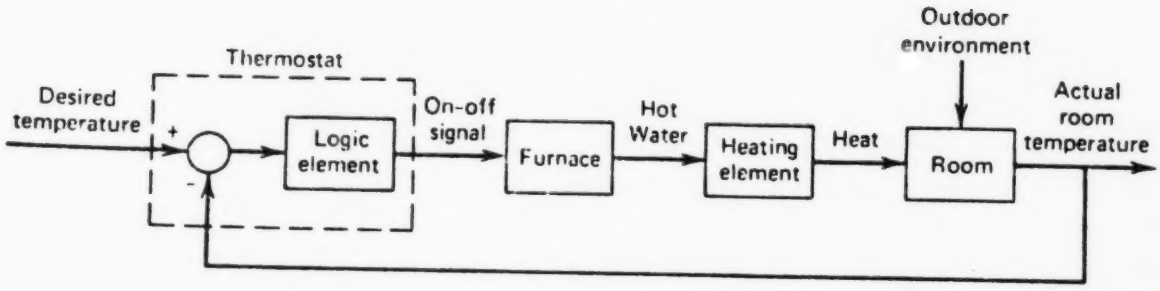



Fig 6: Block Diagram of Temperature Controller.

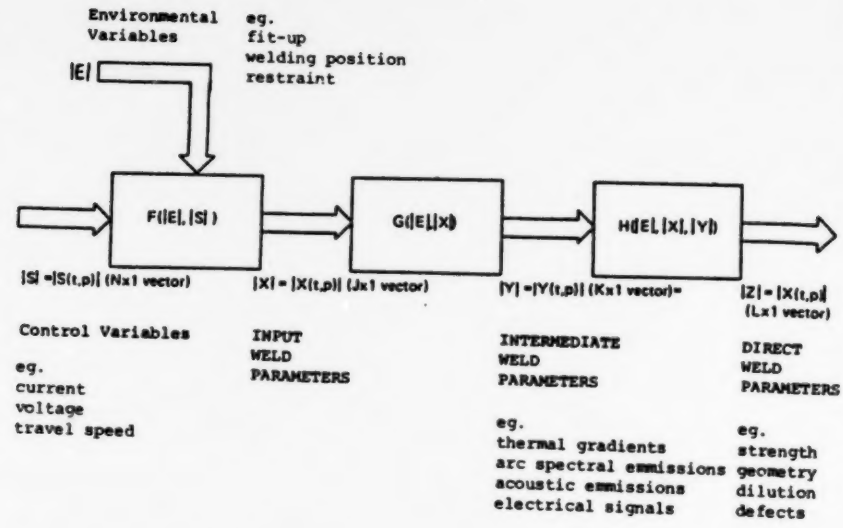



Fig 7: Block Diagram of Open-Loop Welding Process

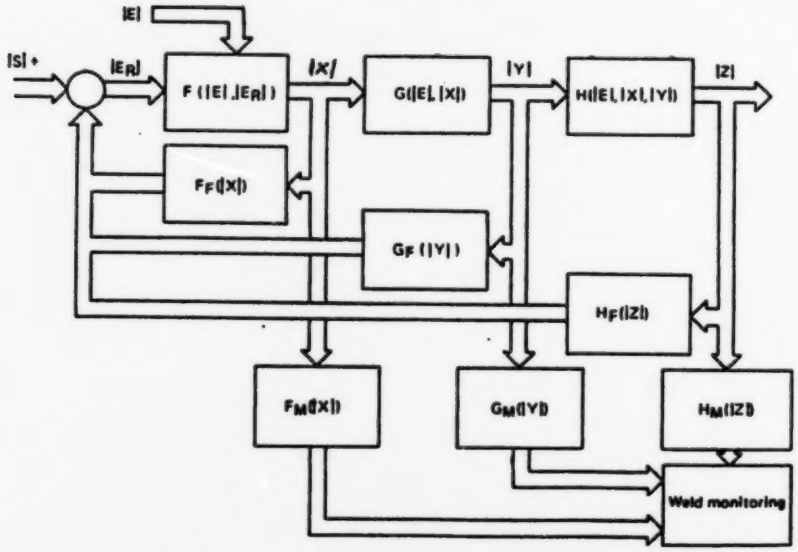



Fig 8: Block Diagram Showing Generalized Feedback and Monitoring of Welding Process Variables

Source: Cook G.E. Proceedings of The Conference on Developments in Mechanized Automated & Robotic Welding. The Welding Institute, Abington, 1980.

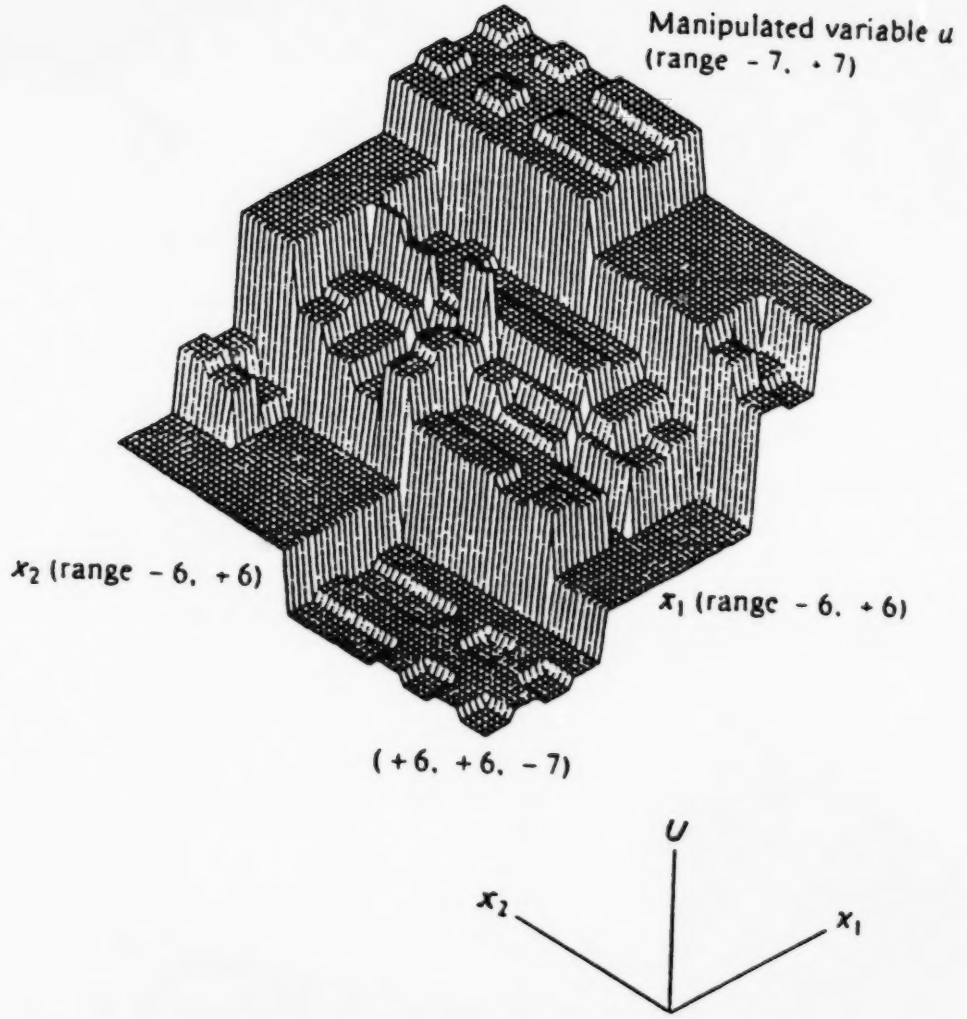
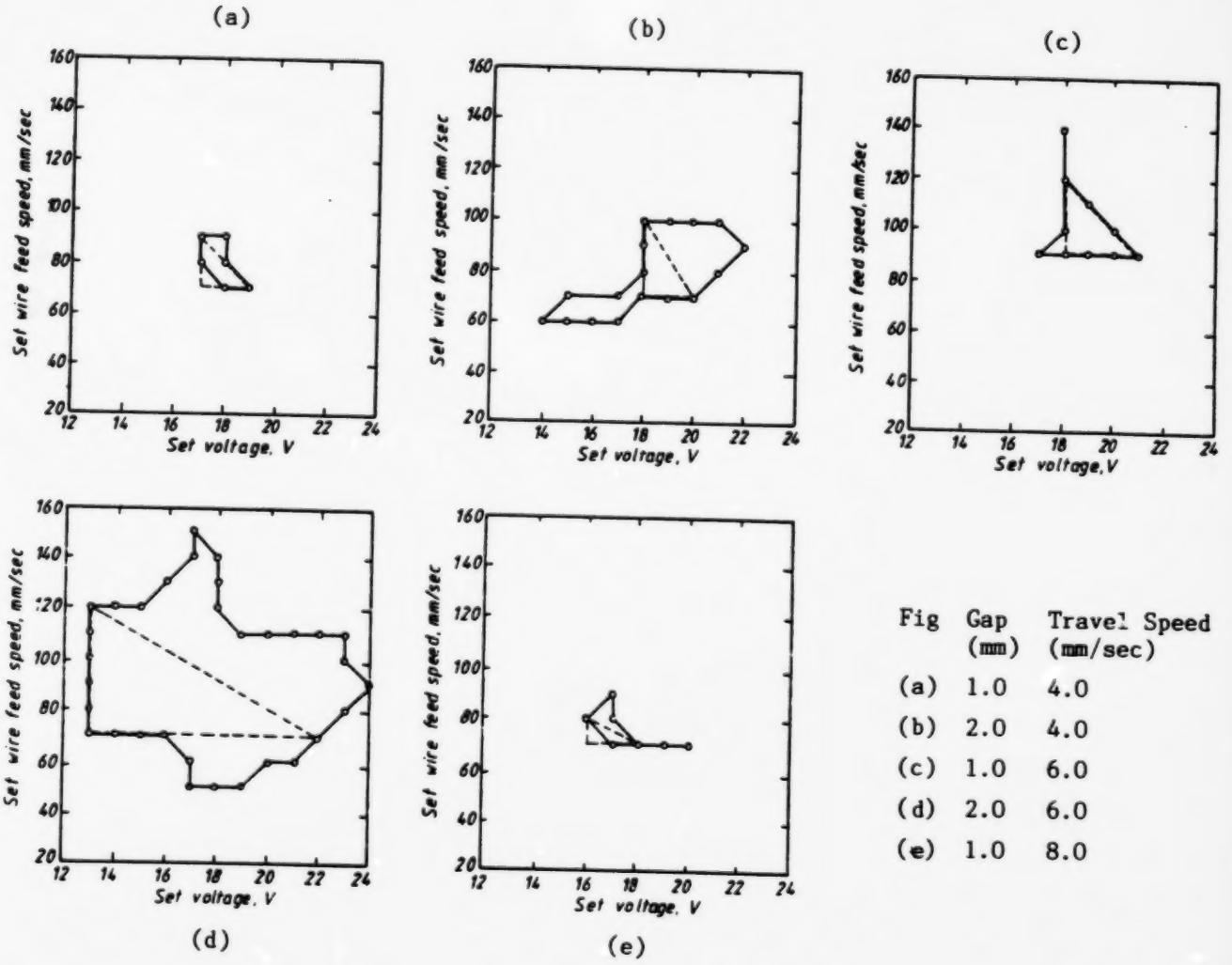



Fig 9: Graphical Model of Controller Showing Required Values of The Manipulated Variable (U) Over a Range of The Independent Variables ($X_1$ & $X_2$).

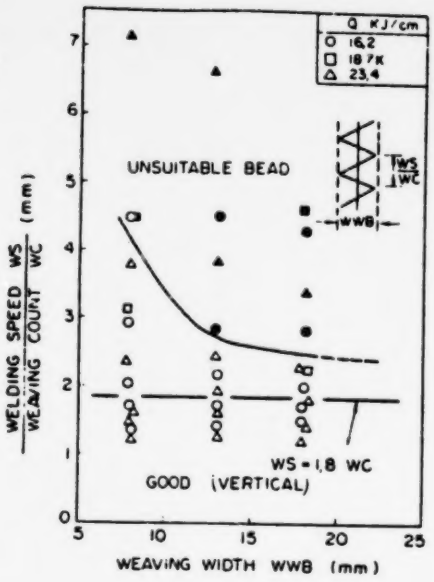
Source: Daley S. and K.F. Gill: Proc. I Mech. E. 19, 9 (1985), No. C1.

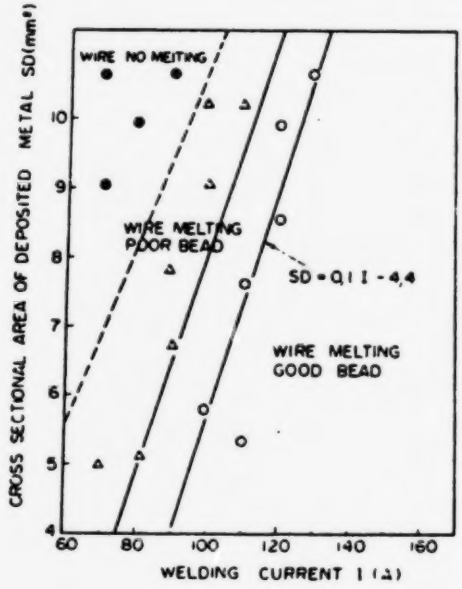


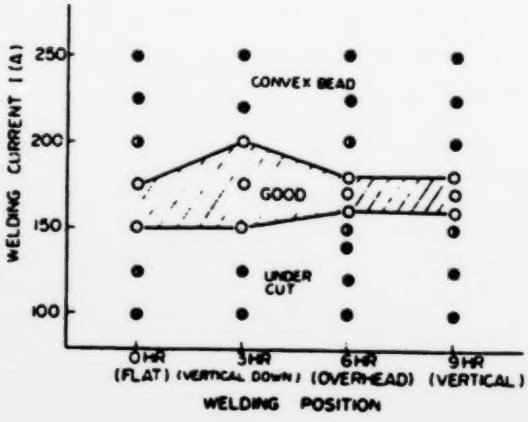

| Fig | Gap (mm) | Travel Speed (mm/sec) |
|---|---|---|
| (a) | 1.0 | 4.0 |
| (b) | 2.0 | 4.0 |
| (c) | 1.0 | 6.0 |
| (d) | 2.0 | 6.0 |
| (e) | 1.0 | 8.0 |

Fig 10: Tolerance Boxes For GMA Welding of Steel Sheet.

Source: Doherty J. and S.J. Holder: Welding Institute Research Members Report 211/1983. The Welding Institute, Abington, 1983.





WIRE NO MELTING
WIRE MELTING POOR BEAD
SD = 0.1 I - 4.4
WIRE MELTING GOOD BEAD
CROSS SECTIONAL AREA OF DEPOSITED METAL SD(mm²)
WELDING CURRENT I (A)



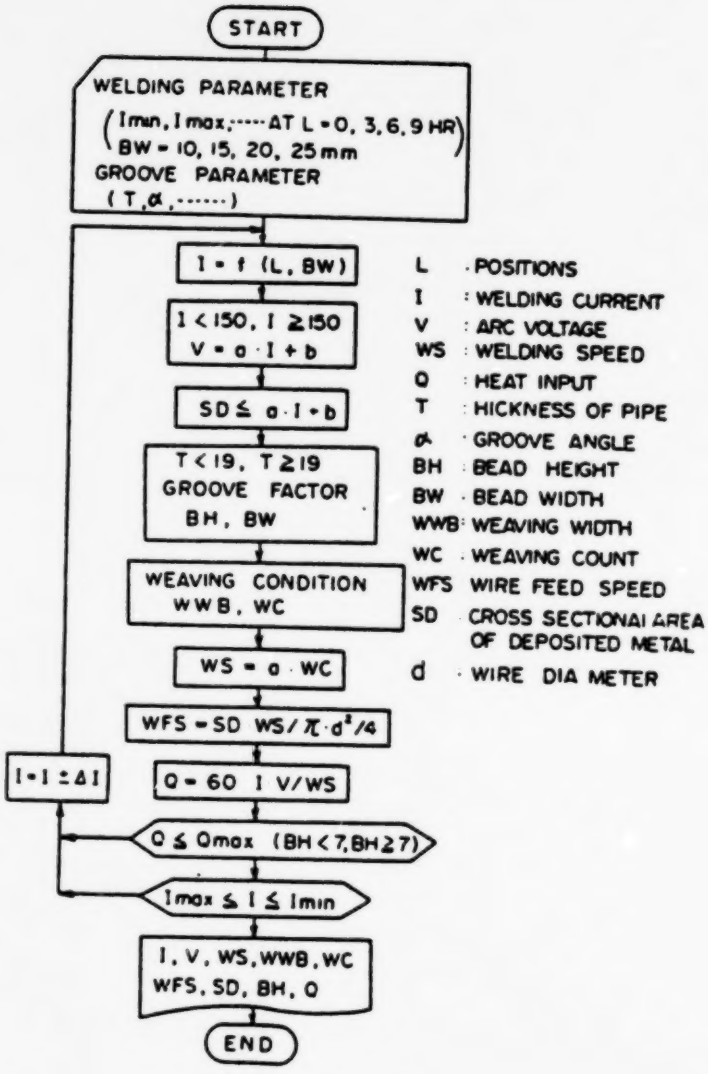


START
WELDING PARAMETER
(Imin, Imax;---- AT L = 0, 3, 6, 9 HR)
BW = 10, 15, 20, 25 mm
GROOVE PARAMETER
(T, α, ------)
I = f (L, BW)
I < 150, I ≥ 150
V = a · I + b
SD ≤ a · I + b
T < 19, T ≥ 19
GROOVE FACTOR
BH, BW
WEAVING CONDITION
WWB, WC
WS = a · WC
WFS = SD WS / π · d²/4
I = I ± ΔI
Q = 60 I V/WS
Q ≤ Qmax (BH < 7, BH ≥ 7)
Imax ≤ I ≤ Imin
I, V, WS, WWB, WC
WFS, SD, BH, Q
END
L · POSITIONS
I : WELDING CURRENT
V : ARC VOLTAGE
WS : WELDING SPEED
Q : HEAT INPUT
T : HICKNESS OF PIPE
α · GROOVE ANGLE
BH : BEAD HEIGHT
BW · BEAD WIDTH
WWB: WEAVING WIDTH
WC · WEAVING COUNT
WFS WIRE FEED SPEED
SD CROSS SECTIONAI AREA OF DEPOSITED METAL
d · WIRE DIA METER

Fig 11: Algorithm for Fill-Pass Control With Supporting Experimental Relations For The Hitachi Automated Pipe Welding System.

Source: Ando S. et al.: Welding In Nuclear Engineering, DVS Berichte, 52, 1978.

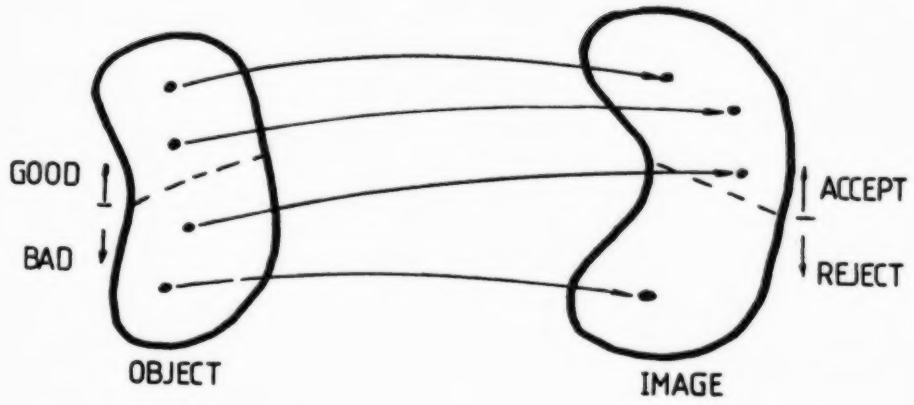
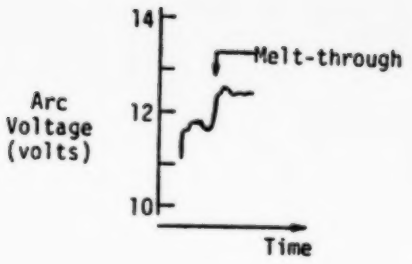
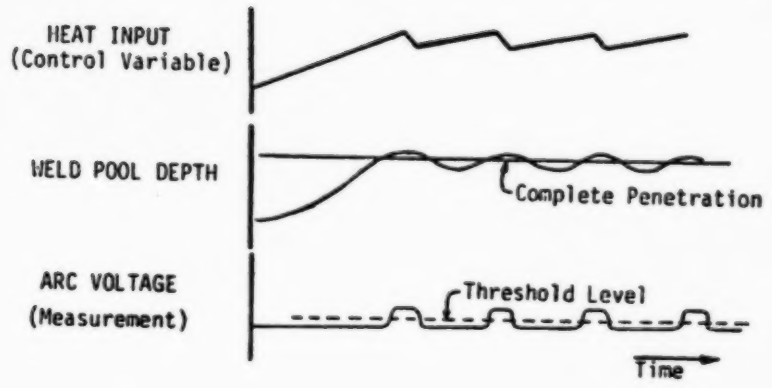



Fig 12: Illustration of Potential Control System Error

(a)




(b)




(c)

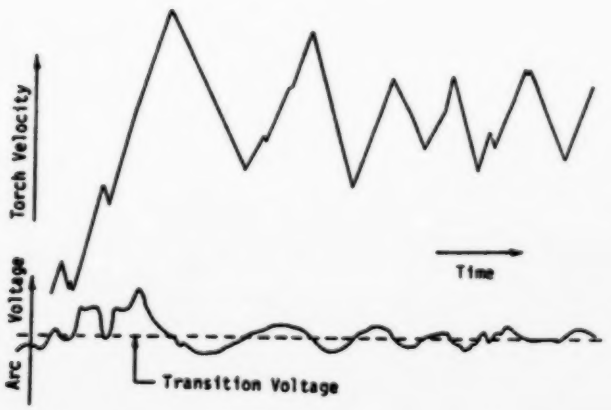



Fig 13: Penetration Control Scheme Using Arc Voltage: (a) Stationary Weld Pool; (b) Illustration of Control Scheme; (c) Record of Torch Velocity and Arc Voltage.

Source: Masubuchi, K. et al.: In Proceedings of The Conference on Trends in Welding Research in the USA. American Society for Metals, Metals Park, 1982.

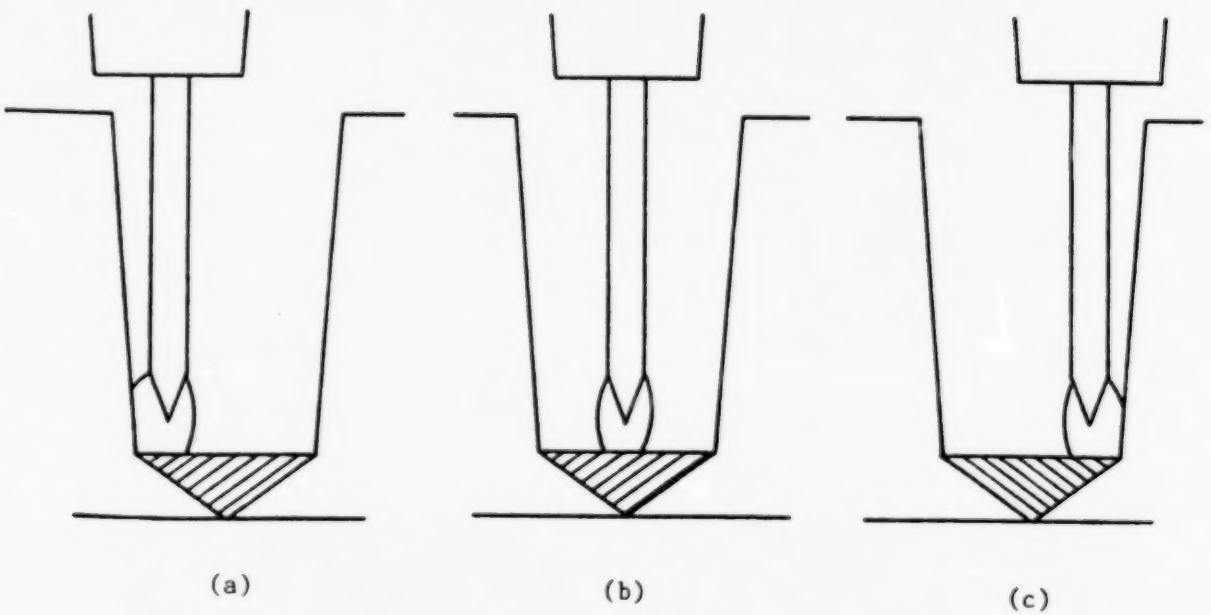



Fig 14: Through-Arc Seam Tracking System: (a) samples taken at left extreme of cross-seam excursion with AVC inactive, (b) AVC activated across width of groove, (c) samples taken for tracking at right extreme of cross-seam excursion with AVC inactive.

Source: Cook G.E. US Department of Commerce NTIS Report NSF/MEA-81004, 1981.

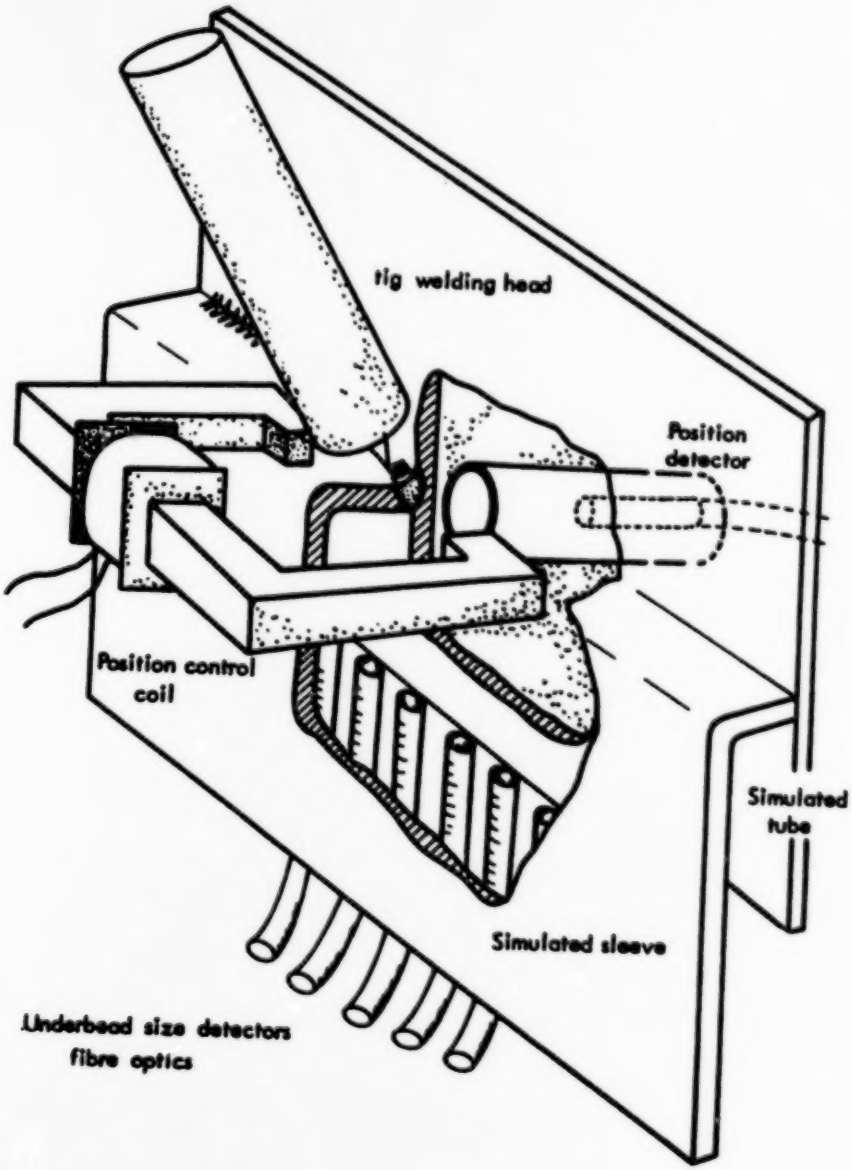
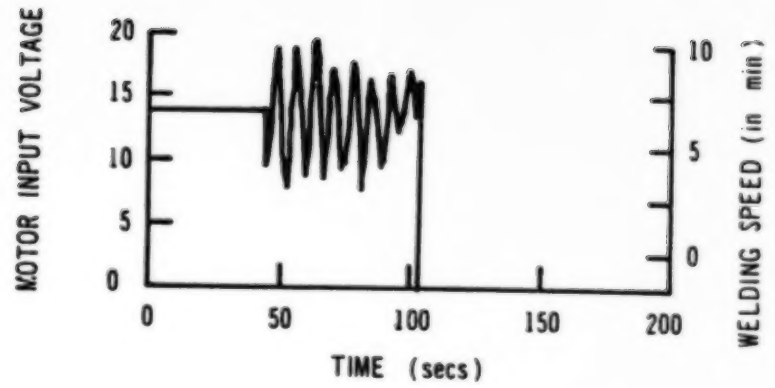



Fig 15: Diagram of Infrared Penetration Sensors for Penetration Control In a T Butt Weld.

Source: Smith, C.: Proceedings of The Conference on Welding and Fabrication in the Nuclear Industry. The British Nuclear Energy Society, London, 1979.

(a)




(b)

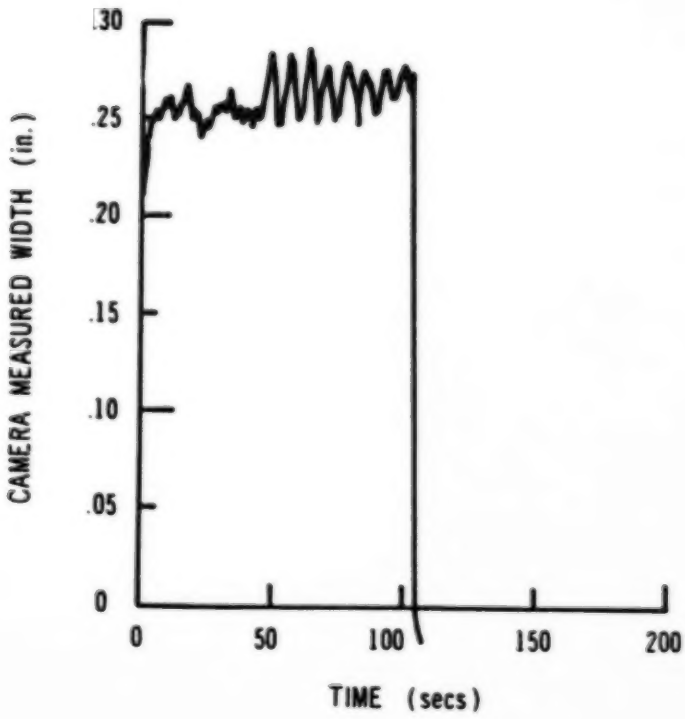



Fig 16: Optical Weld Width Control: Record of Welding Speed (a) against Camera Measured Width (b).

Source: Vroman, A.R. and H. Brandt: Weld. J. 55, 9 (September 1976).

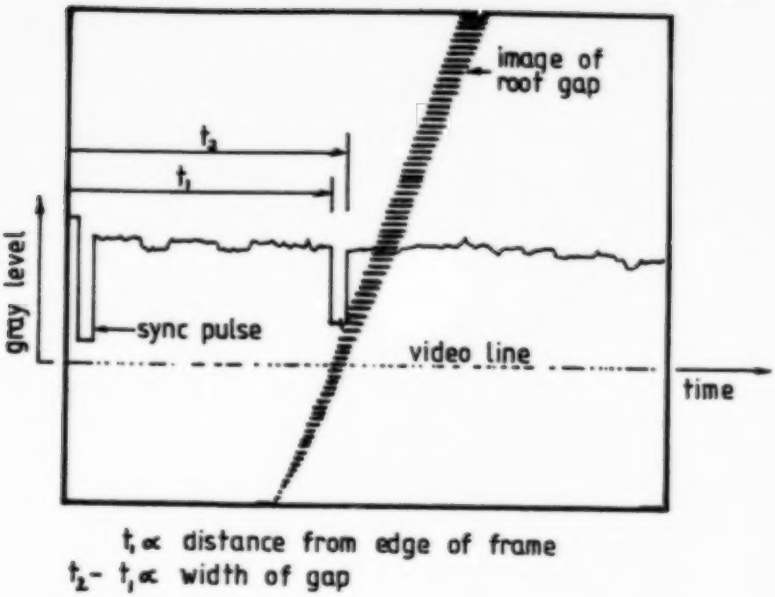



Fig 17: Illustration of Video Image Analysis Technique to Detect High-Contrast Features Such As A Root Gap.

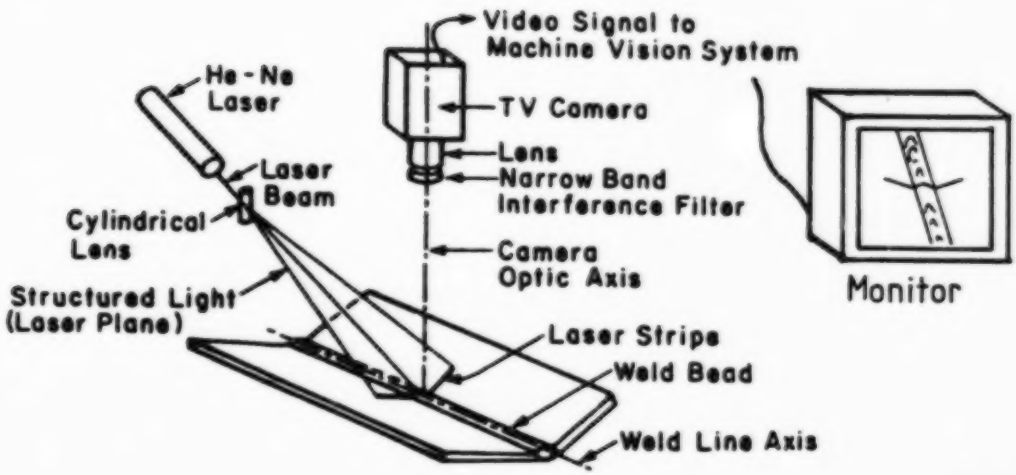



Fig 18: Light Sectioning Technique For Providing Depth Information in a Video Image

Source: Agapakis J.E. et al.: Proceedings of the Conference on Automation and Robotisation in Welding and Allied Processes, The International Institute of Welding, London, 1985.

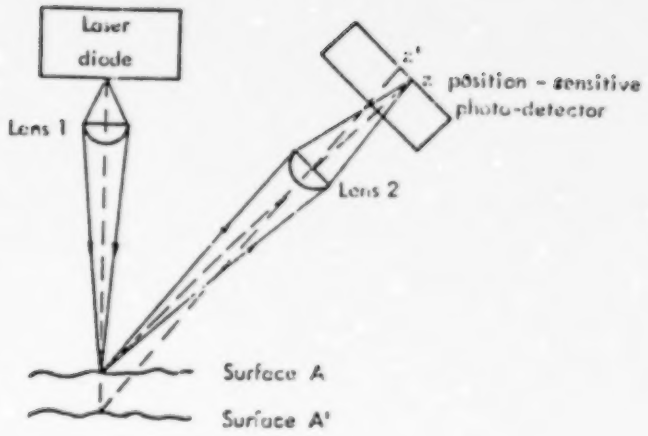



Fig 19: Illustration of The Principles of Laser Triangulation.

Source: Smati Z., et al. Proceedings of the British Industrial Robot Association 6th Annual Conference, 1980.

Fig 20: Illustration of Output From Laser Triangulation Device (a) With Various Degrees of Smoothing (b) Valuation of Slopes Algorithm For Detecting Groove Edges.

Source: Smati Z., et al.